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RESEARCH ON HEADS UP AND HELMET MOUNTED SYMBOLOGY

FINAL REPORT

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OBJECT-BASED ATTENTION AND THE DEVELOPMENT OF HEADS-UP DISPLAYS

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ABSTRACT

The goal of the present research was to articulate, develop and assess an object-based attention framework for researching and designing HUD symbology. The theoretical, empirical and neuropsychological foundations of an object-based attention framework are summarized and linked to research on HUD symbology. It is shown that an object-based attention framework can be used to address and examine a variety of core issues concerning the use of HUDs in aircraft. A series of five experiments are presented in which a framework is established for examining object-based attention effects in visual displays.

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OBJECT-BASED ATTENTION AND THE DEVELOPMENT OF HEADS-UP DISPLAYS

A variety of helmet mounted displays (HMDs) have been proposed to aid pilots when flying in degraded visual conditions. These include light intensifying night vision goggles (NVGs), forward looking infrared (FLIR) systems, and enhanced synthetic visual systems (ESVS). In all of these devices, there is a requirement to include heads-up displays (HUDs) where symbology concerning aircraft orientation, system status, and energy state is projected onto the HMD. It is not at all clear, however, how HUD symbologies should be represented on HMDs nor how these symbologies should be configured, grouped, and referenced. One reason for this is that HUD symbology has often been researched and developed in a theoretical vacuum and without due consideration of human perceptual/cognitive abilities and limitations.

The goal of the present research was to articulate, develop and assess an object-based attention framework for researching and designing HUD symbology. Section one of this report is devoted to the theoretical and empirical foundations of the object-based attention framework. In Section Two, a series of experiments are presented in which a framework is established for examining object-based attention effects in visual displays.

SECTION ONE: THEORETICAL AND EMIPRICAL FOUNDATIONS OF AN OBJECT-BASED ATTENTION FRAMEWORK

1. ATTENTION AND OBJECT PERCEPTION IN HEADS-UP DISPLAYS

1.1 Head-Up Displays (HUDs)

Traditionally aircraft have been equipped solely with head-down displays (HDDs) where the aircraft's cockpit instrumentation (the "near domain") is located about 10° below the pilot's forward field of view (the "far domain"). This configuration precludes the possibility of pilots simultaneously foveating the aircraft's instrumentation and the outside scene. There are many missions, however, when pilots need to maximize time looking outside the cockpit ("eyes out" time) while also closely monitoring the aircraft's instrumentation for flight and power information. For example, during low-level flight pilots need to concentrate on the external scene while frequently cross-checking the cockpit instrumentation for altitude, airspeed, as well as power, navigational, and communication information. Switching between the external scene and the cockpit instrumentation is time consuming and effortful and is likely to diminish the pilot's situational awareness: The information processing stream is interrupted during ocular saccades and often during rapid head movements, thereby inhibiting pilots' ability to build up a stable and accurate mental representation of the flight environment.

The problem of switching viewpoint between the outside scene and an HDD is often exacerbated when pilots are equipped with HMDs. For example, with binocular NVGs, pilots must look under the goggles in order to view the cockpit instrumentation. Re-accommodation of the eye is required when the pilot switches fixation between the NVG far domain and the near domain of the HDD. For fully immersive HMDs, such as those proposed for ESVS, pilots do not have visual access to the cockpit instrumentation.

HUDs of instrumentation symbology have been developed as an alternative to the traditional HDD. HUDs are either located in a panel that is fixed in the forward, heads-up, view of the pilot or superimposed on a HMD. A presumed advantage of HUDs is that pilots should be able to simultaneously access the instrumentation symbology while looking out at the external scene. Accordingly, HUDs should enhance situational awareness by eliminating (or greatly reducing) the need for pilots to repeatedly switch between a head-up/eyes-out viewpoint to a head-down/eyes-in viewpoint. To this end, numerous studies have shown a benefit of HUDs over the traditional head down displays (HDDs). For example, McCann and Foyle (1996) showed that (a) pilots are able to control an aircraft's flight-path better with HUDs than with standard HDDs and (b) pilots are faster in responding to events located in either the far or the near domain when using a HUD rather than a HDD. There is also some evidence that pilots are better at tracking flight guidance symbology such as airspeed and altitude with HUDs than with HDDs (Martin-Emerson & Wickens, 1997).

1.2 Attentional/Cognitive Tunnelling

Although HUDs may enhance performance by allowing pilots to maintain a heads-up field of view, there are also situations were HUDs have been shown to result in performance decrements due to attentional/cognitive tunnelling. Some of these attention-based performance decrements have serious implications for flight safety.

Fisher, Haines and Price (1980) described a simulator-based experiment where pilots were required to perform runway approaches flying an aircraft that was equipped with a HUD versus a traditional HDD. It was found that some of the pilots using the HUD failed to notice unexpected intrusions on the runway when they were also required to attend to events in the near domain (see also McCann & Foyle, 1996). This failure to notice runway intrusions was not experienced by pilots using the HDD. Although suggestive, the Fisher et al. study was flawed in that the location of the instrumentation (HUD vs. HDD) was confounded with the type of instrumentation.

Wickens and Long (1994) repeated the Fisher et al. (1980) experiment but with matched instrumentation across the HUD and HDD. In contrast to the Fisher et al. findings, pilots using the HUD were successful in noticing runway intrusions. However, these pilots were considerably (2.5 sec.) slower to respond to intrusions than were pilots using the HDD. In sum, both the Fisher et al. (detection accuracy) and the Wickens and Long (detection time) studies show a disadvantage for HUDs versus HDDs. This disadvantage seems to arise in situations where the pilot has to simultaneously attend to information located on the HUD and in the external scene.

The disadvantage of HUDs is further illustrated in a study by Foyle, Stanford and McCann (1991) who required pilots to control their flight-path while maintaining a fixed altitude. Superimposing a HUD digital readout of altitude onto the flight path resulted in excellent control of altitude. However, when focusing on altitude, pilots tended to collide with the flight-path markers, such as buildings or landmarks. This trade-off between using the HUD symbology (digital altitude) and processing of the external scene cannot be attributed to visual interference or masking: The same HUD symbology was presented across the various conditions. Instead, this evidence suggests that when the HUD symbology is required for performance, the symbology tunnels the pilot's attention at the cost of unattending to object and events in the environment. That is, when focusing attention on one domain, information located on the other domain tend to go unnoticed. This phenomenon has been labelled cognitive tunnelling (Martin-Emerson & Wickens, 1997; Wickens & Long, 1995). Cognitive tunnelling with HUDs is driven by attentional mechanisms where a pilot's awareness of the far domain (external scene) is reduced when attending to the near (HUD) domain. Accordingly, insight into the mechanisms underlying cognitive tunnelling on HUD symbology (and how to prevent tunnelling) requires an understanding of the role that attention plays in human information processing.

1.3 Attention And The Perceptual Grouping Of Symbology Into Objects

A growing body of research in the HUD literature can be linked to evidence from basic research showing that attention is referenced to perceptual groups or objects within the visual field (Duncan, 1984; Baylis & Driver, 1989; Kramer & Jacobson, 1991). This is known as the object-based attention hypothesis.

It is generally accepted that a perceptual object or group is formed according to the Gestalt grouping principles of motion, colour, proximity, closure and/or figure-ground separation (Koffka, 1935). According to this definition, objects can be something as simple as features moving together against a background of static features (Baylis & Driver, 1988), or an object can be formed by a simple pattern that is determined by closure, proximity or colour. A perceptual object can also consist of a more coherent form involving more than one grouping principle.

Research has shown that it is easier to attend to a single object within the visual field than it is to divide attention between two separate objects. Attending to a single object may also allow for parallel processing of all features of that object, whereas features belonging to two separate objects are processed serially (Baylis & Driver, 1993; Goldsmith, 1998). This evidence for object-based attention has led researchers to claim that the attentional problems experienced with HUDs are due to the near and far domains forming separate perceptual groups. This claim is predicated on the notion that near and far domains differ along one or more of the Gestalt grouping principles. In particular, the HUD symbology is stationary relative to the pilot- or aircraft-centric view, whereas the external scene is in constant motion. Also, HUD symbology is usually displayed in a uniform colour, which may differ from the various colours of the external scene.

The claim that the near (HUD) and far (external scene) domains form separate perceptual groups provides a possible explanation of cognitive tunnelling when combined with the object-based hypothesis. On this view, when pilots attend to the near domain, all of the HUD symbols get processed quickly in parallel while processing of information in the far domain is delayed.

Martin-Emerson and Wickens (1997) examined the difference in the use of HUDs versus HDDs across different visibility levels. As pilots came in for an approach to land under different visibility conditions they had to hold a stable altitude and control lateral and vertical tracking. Flight path guidance was superimposed onto the path for the HUD condition and located below the windshield for the HDD condition. The results showed that for the HUD condition pilots were faster to respond to events within the HUD display and to control altitude when under zero visibility as compared to full visibility conditions. In full visibility pilots attend to the far domain, thereby making it more difficult to control the altitude and respond to events occurring in the HUD. However, lateral and vertical tracking errors also decreased in the full visibility condition. According to Martin-Emerson and Wickens this was due to pilots switching attention to the far domain in the full visibility condition. However, because pilots had to hold altitude and respond to events within the near domain, it is unlikely that they switched attention completely toward the far domain. Indeed, it is possible that the pilots successfully integrated the HUD flight-path symbology with the external environment but experienced difficulty attending to other information located in the HUD. That is, although this evidence fits with the object-based hypothesis that attention is difficult to divide across near versus far domains, it can also be interpreted as indicating a difficulty in integrating information within a single domain.

McCann, Foyle & Johnston's (1993) finding that responses to targets were significantly delayed when a cue was presented to the nontarget domain could be interpreted as showing that near (HUD) and far (external scene) domains form separate visual objects. In accord with the object-based attention hypothesis, target responses are slower when the cue occurs in the nontarget domain because it takes time to switch attention from one object (domain) to the other. However, a careful review of the McCann, Foyle & Johnston procedure leads to an alternative explanation. In this experiment, pilots were required to perform an approach to land. As they approached landing, a three-letter cue ("IFR" or "VFR") appeared either on the HUD or on the runway (external scene). The cue indicated where to look for a target among several geometric symbols that appeared on both the HUD symbology set and the runway. "IFR" (for instrument flight rules) indicated that the set of symbols on HUD was relevant. "VFR" (for visual flight rules) indicated that the set of symbols located on the runway was relevant. The pilots were required to identify whether one of the symbols (the target) was a diamond or a stop sign: A landing was allowed only if the target was a diamond. Four boxes were located on the HUD to flank either side of the runway and another four boxes were superimposed onto the far domain in a similar position. The distance between the boxes was equal for both domains. The three geometric symbols appeared in three of the boxes on each domain and the cue would appear in the fourth box on either the near or the far domain. If the cue appeared on the HUD it filled the box in either the bottom left or the bottom right corner. If the cue appeared on the runway it filled either the top left or the top right box.

The results showed that subjects were significantly slower in responding to the relevant target when the target and the cue where located on different domains. For example, when the "IFR" (indicating that target on the HUD is the relevant one) appeared in the display, pilots were faster to respond to the target when it was located on the HUD than on the runway.

As noted above, the object-based attention interpretation of the McCann, Foyle & Johnston (1993) result is that the near and far domains form separate visual objects: It takes time to switch attention from one object to the other. However, another plausible interpretation is that the slower responses in the cross-domain condition are due to there being two different types of cues. The sudden onset of the three letters is a form of exogenous cueing that immediately draws attention to that location. In contrast, the interpretation of the three letters is a form of endogenous cueing: the participants had to interpret the meaning of the three letters to determine the relevant target location. Attentional allocation is much slower with endogenous cues than with exogenous cues:

whereas attentional allocation can occur within 100 ms with exogenous cues (Wright & Ward, 1998), the allocation of attention with endogenous cues can require 300 ms and longer (Stelmach, Campsall, & Herdman, 1997). On this view, when "IFR" was shown on the HUD, the pilots would be able to determine almost immediately whether the target on the HUD was a diamond or stop sign: there would be no need to interpret the cue itself. Accordingly, when the symbolic cue concurred with the direct cue, pilots were fast to respond. When the symbolic cue did not concur with the direct cue (a different location of the relevant target was indicated versus the direct cue), then responses were slow.

In sum, the Martin-Emerson and Wickens (1997) and the McCann, Foyle & Johnston (1993) experiments suggest that attention limits the ability of pilots to process HUD symbology simultaneously with information in the external scene. The results of these experiments have been explained using an object-based attention hypothesis, on the assumption that the near and far domains form separate perceptual groupings. However, lack of definition of the concepts involved in the object-based hypothesis makes it hard to avoid possible confusion with other factors that may influence attention. For example, the results in the McCann et al. study can be interpreted in terms of spatial cueing rather than perceptual grouping. Also focusing entirely on near versus far domains as the relevant "objects" in attentional control limits the application of the object-based attention hypothesis. To wit, in the Martin-Emerson and Wickens study, performance changes may be attributed to attentional difficulties in integrating information within the near domain. It is important, therefore, to further develop the object-based framework in order to systematically study the information processing difficulties in HUDs.

1.4 Conformal Symbology

As mentioned above, most research on HUD symbology has proceeded on the assumption that the HUD symbology and the external scene form two distinct perceptual groups or domains. Accordingly, it has been suggested that fusing the HUD and external scenes may provide a way to facilitate the dividing of attention between the domains. One way of doing this is to use conformal symbology. Broadly speaking, the definition of conformality used by HUD developers refers to the degree to which a symbol forms an object within the scenery. The idea is that a conformal symbol should serve as a virtual analog for far domain elements. In other words, symbology that is an accurate graphic representation of an actual object represented in the far domain, or that forms a one-to-one correspondence with the world is deemed to be conformal (Martin-Emerson & Wickens, 1997). On this view, conformal symbology can be a virtual runway overlaying the actual runway or a scene-linked symbology where, for example, altitude is represented at the height of and possibly in actual objects in the far domain. Non-conformal symbology would be symbols such as a digital readout of the altitude or airspeed, path guidance information like glide slope, or localizer symbology (Wickens & Long, 1995). It should be noted that according to this definition, even traditional HUDs have some conformal symbology (e.g., a horizon line). In contrast, symbols representing VSI, airspeed, distance, and altitude etc. are usually non-conformal.

Experiments examining conformal symbology in HUDs have yielded promising results. For example, research by Foyle, Stanford and McCann (1991; see also McCann & Foyle, 1994) has shown that when using conformal symbology pilots are able to maintain altitude and follow a flight path without significant trade-offs in performance. In these studies, altitude symbology was rendered conformal by placing the symbology on virtual buildings along the flight path. In contrast, when the altitude indicator was superimposed onto the path (non conformal) the task of maintaining altitude reduced flight path performance.

Varying the form of the conformal symbology does not seem to diminish the enhanced performance. McCann and Foyle (1995) and Shelden, Foyle and McCann (1997) have shown evidence for the same benefit of conformal symbology over non-conformal symbology regardless of whether the form of the symbology was analog ("clockface") or digital. These experiments are quite promising and suggest that the conformal character of the HUD symbology presumably enables parallel processing of information from the two domains. In accord with an object-based hypothesis, conformal symbology might allow for the creation of a single far domain (or object layer) of information. On this view, performance is enhanced because the pilot is able to allocate attention to the far domain without the need to switch to the near domain.

Although the Foyle, Stanford and McCann (1991), McCann and Foyle (1994;

1996) and the Shelden, Foyle and McCann (1997) research on conformal symbology has yielded promising results, the experimental designs that have been used in this research are flawed. In particular, adding elements onto the flight path, whether those elements are virtual buildings or numbers, increases the number of cues that the pilot can use to control the aircraft's flight path. Accordingly, the enhancement in timesharing the flight-path task and the symbology-based tasks may not be due to a reduced requirement to switch attention across domains. Instead, this enhanced dual-task performance may be attributed to the reduced load associated with controlling the aircraft's flight path when more path cues are present.

In another experiment, Martin-Emerson and Wickens (1997) tested the difference between conformal and non-conformal HUDs using symbology that differed only in terms of path guidance information. Both conditions included non-conformal symbology such as VSI, heading, speed, and distance. In the conformal condition, a virtual runway overlaying the actual runway provided path guidance. In the non-conformal condition, path guidance was represented by a localizer and a glide slope, a fixed aircraft symbol and a reference line. The subjects' task was to approach to land under different visibility conditions. The results showed that for the non-conformal condition there was large variance in lateral tracking errors depending on visibility. In comparison, when pilots used the conformal symbology the lateral tracking errors were undifferentiated across the different levels of visibility. For the vertical tracking errors symbology had no effect. What makes these results interesting is that if the problem with non-conformal symbology is that pilots cannot process information in both near and far domains in parallel, then conformal symbology should have shown benefits for both vertical and lateral tracking. There are, of course, important differences between vertical and lateral tracking tasks. Lateral tracking is more difficult and often involves turbulence. It is possible that the benefit for lateral tracking when pilots used conformal symbology reflects a more intuitive method of control.

In sum, the use of conformal symbology is promising in that it reduces the performance tradeoffs found with HUDs. It is important to note that the object-based attention hypothesis can be applied to the Martin-Emerson and Wickens (1997) results although not necessarily under the assumption that conformal symbology fuses the two domains into a single perceptual group. For example, it could be argued that conformal symbology leads to better performance because the symbology forms a coherent object in and of itself. In accord with the object-based attention hypothesis, a sense of objectness presumably makes it easier for pilots to attend and process information within the conformal symbology. That is, the advantage of conformal symbology may not be due to the notion that the symbology is integrated into the external scene, as is commonly assumed, but instead attributed to the facilitory effects of object-based attention.

1.5 Visual Clutter

The object-based attention framework applies not only to the issue of simultaneously attending to the near and far domains, it is also implicated in the processing of symbology within a particular domain. Individual elements in cluttered displays are more difficult to locate, attend, and interpret. As a result, attending to one particular element is often accomplished at the cost of interference form other elements (Martin-Emerson & Wickens, 1997). It might be the case that making a particular element more object-like makes it easier to attend to that element and filters out interference from neighbouring elements. Also, the sheer number of symbols in many symbology sets can make it difficult to integrate relevant information coming from various elements, or to organize the elements so as to optimise the visual interrogation of these elements. Principles of perceptual grouping might facilitate the organization of a cluttered display into usefully related sub-groups.

Integrating conformal symbology into the external scene, which has been suggested as a potential solution to the tunnelling problem, can reduce the level of clutter in the near domain, but in turn will increase the number of elements in the external scene. The full impact of transferring elements from the near to the far domain is unknown. As noted above, studies have shown that there is a similar delay in responding to unexpected runway intrusions regardless of whether the symbology is conformal or non-conformal (Martin-Emerson & Wickens, 1997; Wickens & Long, 1995). Foyle et al, (1993) showed that locating an altitude indicator directly on the flight path and in the centre of the field of view, resulted in a performance trade-off between maintaining a set altitude and staying close to a flight path. When the altitude indicator was located above and to the side of the flight path there was no performance trade-off: pilots were able to process the HUD altitude symbology and follow the flight path successfully.

In sum, the object-based hypothesis provides a framework that can be applied not only to the problem of dividing attention between the two domains but also to investigate the notion that information within a domain can be processed and integrated more effectively.

1.6 Summary

Object-based attention has been implicated in research aiming to explain problems associated with information processing within HUDs and HMDs. These explanations have generally been predicated on the assumption that the HUD symbology (the near domain) forms one perceptual group, and the outside scene (the far domain) forms another group. Thus, the problem of dividing attention between the near and far domains has been explained by claiming that one of the domains, usually the symbology set, captures attention at the expense of the other, a phenomenon referred to as cognitive tunnelling. Similarly, the presumed benefits of conformal symbology have been explained by claiming that conformal symbology allows the fusion of the near and far domains into a single perceptual group.

Although the object-based attention hypothesis has received support from basic research on attention, the hypothesis is still relatively undeveloped. Therefore the application of the hypothesis within the aviation literature has been problematic. One problem is that there appears to be a tacit assumption in the literature that the only 'objects' that attention selects are the near and far domains; the study of object-based effects within a domain has so far been neglected. For instance, it is possible that the benefits accruing from the use of conformal symbology may be due to the symbology forming more coherent visual objects, rather than to a presumed fusion of the near and far domains. Similarly, the problem of visual clutter in symbology sets might be best studied by examining how users group the symbols within the set. Indeed, the assumption that the display contains two perceptual domains has added little to our understanding of visual clutter. Moreover, the study of these issues is complicated by a number of confounds. For instance, the McCann, Foyle and Johnson (1993) study shows that object-based factors can easily be confounded with spatial cueing. Similarly, object-based factors can be confounded with the informativeness of the symbology, as is the case for the use of scene-linked symbology in the study by Foyle, Stanford and McCann (1991).

To a large degree, these problems are due to the fact that the definition of 'object' and 'perceptual group' is vague; this has prevented a proper account of the distinction between spatial and object-based factors, and of their interaction, in visual attention. Precisely what these concepts mean in the context of the attentional problems experienced by HUD users needs to be more fully articulated and examined. Perceptual groupings or objects are typically defined by Gestalt grouping principles of motion, colour, proximity, closure and/or figure ground. The instantiation of Gestalt grouping principles during the use of dynamic displays (e.g., HUDs) has been relatively unexplored and several important questions concerning perceptual grouping need to be addressed. For example, it is not clear whether there is a hierarchy of grouping principles where one perceptual grouping principle overrides others. If a hierarchy exists, is it stable or fluid? With complex displays, it is not known whether a single grouping principle is sufficient for forming a single object or whether more than one grouping principle must be put into place. It is possible that the addition of a second grouping factor to a HUD symbol will enhance the sense of the symbol's objectness. It is not clear, however, whether the extent of a symbol's "objectness" is related to degree of object-based attention assigned to the symbol. This is important to determine because a HUD symbol that is perceived as a strong object may impact on cognitive tunnelling.

2. METAPHORS AND MODELS OF SPATIAL ATTENTION

The framework that is being proposed here focuses primarily on object-based attention for the evaluation of the design of HUD. However spatial factors like the effect of cueing also play a role in the controlling of attention in HUD. It is therefore important for establishing such a framework to not only understand the principles that underlie the object effect but also how object-based and spatial factors differ and how they may interact in their control and maintenance of attention.

2.1 Background

Attention is a fundamental topic in cognitive psychology and it is a topic that has been raised extensively in human factors research. However, despite the fact that numerous models of attention have been proposed over the years, there is still much confusion as to what attention is and what it does. Clearly, a primary role for attention is that of selectively enabling processing of "privileged" information. But this is by no means the only role. Attention serves to enhance neural information processing, modulate motor responses to stimuli, and to maintain working memory and the sequencing of cognitive operations. Attention also is necessary for the binding together of perceptual features into a single phenomenal object or percept (Treisman, 1983; Treisman, 1988; Treisman, 1998; Treisman & Gelade, 1980). Attention also allows an organism to select a relevant mental representation of the environment to guide further action (Tipper & Weaver, 1998).

The contrast between the Treisman (1983) and the Tipper and Weaver (1998) views is interesting. While both assume that attention operates on mental representations, Treisman contends that attention is necessary to form a coherent representation of something, while Tipper and Weaver take some form of completed representation for granted and assume that attention selects a given representation. This contrast is very informative, because it illustrates one of the fundamental tensions in the attention literature: does attention serve the role of integrating and processing perceptual information into coherent representations, or does it simply select "pre-formed" representations for further processing such as decision-making and action? This has been expressed in the literature in many ways, the most prominent being the debates on early vs. late selection and on spatial vs. object based attention. In both of these debates, one camp assumes that perceptual processing (i.e. the creation of percepts that later become representations of the environment through object recognition) requires attention to happen; this is the case for the early selection and the spatial models of cognition. The other camp assumes that some degree of perceptual processing (shape identification, object recognition) has occurred before attention is directed to visual stimuli, and that attention simply serves the purpose of selecting one of these representations; the late selection and the object-based attention send to fall into this category.

2.2 Models Of Spatial Attention

Assumptions about cognition and attention have been combined to produce several different metaphors of spatial attention. These metaphors get cashed out as a variety of different models by various researchers. However, it is useful to review the metaphors as each one illustrates a basic set of more-or-less orthogonal assumptions that have informed the more detailed models. Moreover, as noted below, the "fit" between the notion of object and spatial attention depends on the particular metaphor of spatial attention that one adopts. This fit will impact on the framework that is used to research and develop HUD symbology.

2.2.1 Attention as a filter

Broadbent's (1958) filter model is one of the earliest attentional metaphors. Broadbent drew inspiration mainly from research into the auditory system and from assumptions underlying information theory. Indeed, the filter model was an attempt to apply information theory, as developed by Shannon (1938), to the auditory system. Broadbent's original filter model had the following features:

- Attention is viewed as a structure of the cognitive system that filters out information. That is, some information is let through the filter for further processing, whereas everything else is simply discarded. What is let through and what is discarded is determined solely on the basis of the physical characteristics of the stimulus.

- Filtering operates right after the basic physical analysis of the stimulus but before any kind of conceptual processing takes place (i.e. before a stimulus is categorized or identified).
- The purpose attention is to limit how much information the cognitive system needs to process at a given time - effectively protecting it from overload - because cognition is seen as being a system with inherently limited resources and abilities for coping with much information at one time.

In sum, the filter metaphor is one where attention facilitates higher-order processing by protecting the system from "information overload" at a very early level. While intuitively appealing, the limitations of Broadbent's metaphor became quickly apparent. First, within auditory research, experimental evidence showed that not all "unattended" stimuli were entirely discarded by the system. Second, research has shown that cueing of a particular region of the display enhanced processing of information at that location. In these cases, since the stimuli to be processed were often the only ones in the display, there was noting else to filter out. Yet, responses were more rapid to cued than to uncued stimuli. These results suggested that a simple filter model was inadequate, that attention plays a role in favouring or enhancing processing at locations in the visual field. Although the filter model has been modified and extended somewhat to deal with new data, the experimental evidence eventually suggested another metaphor: the attentional spotlight.

2.2.2 Attention as a spotlight

There are two version of the spotlight metaphor, both of which are based on the notion that attention "highlights" a region of the visual field. One version of this metaphor is similar to the filter metaphor in that what falls outside of the attentional spotlight is presumably not processed (Posner, 1980; see also Fernandez-Duque & Johnson, 1999). In the second version, the spotlight serves to concentrate attentional resources to a particular region space, thereby enhancing processing at that location, but without completely eliminating processing of the unattended regions (Downing & Pinker, 1985; Jonides, 1981).

In either version, however, the spotlight metaphor differs from the filter metaphor in several important respects. First, the attentional filter is viewed as a structure through which information must flow. In contrast, the attentional spotlight is not a structure but rather a functional enhancement of information flow. A corollary to this is that where the filter simply blocks unwanted information, the spotlight "selects" and enhances information in a given spatial region of the visual field. The spotlight does not set things aside but "takes what it needs". Second, the spotlight has a spatial dimension that the filter lacks: the spotlight selects a region of space, whereas the filter is insensitive to the spatial layout of information. Third, whereas the filter is simply a passive mechanism that sits at the front end of the information chain, the spotlight can be controlled. In particular, the spotlight can be moved to different parts of the visual field and, according to some specific models, the size and possibly the shape of the spotlight can be changed. This flexibility raises the issue of what controls the spotlight, which didn't emerge with the filter metaphor.

In sum, the attentional spotlight metaphor improves on the filter metaphor in that it allows for the notions of enhancement of information processing (crucial to cueing data) and of a measure of control over what information gets selectively processed. Most of the early spotlight models included the assumption that the spotlight can not be split between separate regions of space. Accordingly, attending across several regions of space required a serial allocation of the attentional spotlight. Later versions of the spotlight model include the assumption that the attentional spotlight can be split among two of three regions of space.

2.2.3 Attention as a spotlight-in-the-brain

Does attention select features of the visual field for further processing, or does it select already-processed representations of the environment for further action? The spotlight-in-the-brain metaphor takes the latter view (LaBerge, 1995). This view does not necessarily follow from the assumption that attention selects objects rather than features. Instead, it is necessary to make the additional assumption that the "objects" being selected are somewhat sophisticated mental representations of objects, rather than simply low-level perceptual groupings that map rather directly onto the visual stimulus.

It is only on the first assumption about the nature of the objects implicated in attention that the spotlight-in-the-brain idea becomes relevant. If the objects in question are simply parts of the visual field grouped and bundled into perceptual wholes, with very little conceptual information attached to them, then an attentional system that is directed to them is for all intents and purposes directed to the outside world. But if the "objects" are abstracted representations of the environment and thus not perfectly correlated with the visual environment, and if these carry conceptual information added by the system (e.g., a person's expectations), then the spotlight-in-the-brain idea becomes more clearly separated from the spotlight metaphor.

Whereas the distinction between the spotlight and the spotlight-in-the-brain metaphors is relatively clear, it is rarely equally clear which of the two a particular researcher is basing their research on. One reason for this is that assumptions as to the nature of objects are rarely made explicit. This can have rather dramatic implications for the research and design of HUDs. In particular, the nature of the "objects" implicated in attention (relatively high-level representations with conceptual content vs. relatively low-level perceptual groupings) has a bearing on what kinds of information will affect the allocation of attention to different parts of a visual scene.

2.2.4 Attention as vision

The filter and spotlight metaphors carry the implicit assumption that perception and attention are separate, with the implication that attention is a modality-independent mechanism that is outside of perceptual mechanisms but which nevertheless modulates perception. This is in stark contrast to the attention-as-vision metaphor, which proposes that visual attention is a property of the visual system itself (presumably with the added implication that each sensory modality its own attentional system) (van der Heijden, 1986).

The basic premise of attention-as-vision metaphor is that visual attention operates in a manner very similar to low-level vision, and that both in fact share many mechanisms. More specifically, the focus of attention is thought to behave like the fovea, and the movements of the focus of attention (i.e. attentional shifts) are thought to be very similar to eye movements (saccades). In fact, according to this hypothesis, attentional shifts and saccades are programmed by the same mechanisms (Sheliga, Riggio, & Ritzolati, 1994). A few assumptions about the nature and role of attention follow from this. First, because the human fovea cannot be split it is assumed that the focus of attention cannot be split. Second, attentional shifts and ocular saccades are thought to be highly correlated. Third, under the attention-as-vision metaphor, attention and perception are very closely linked, operating virtually simultaneously. On this view, the purpose of attention is to enhance perception and to guide (target) eye movements.

It's not entirely clear how this attention-as-vision metaphor relates to spatial-based versus object-based models of attention because the metaphor stakes no claim as to what is being attended to, beyond the visual scene itself. However, there are some links that can be made. For example, the unitary fovea is reminiscent of the claims made by some spatial attention theorists that the spotlight cannot be split. On the other hand, the close link between perceptual processes and attention is not entirely unlike the claims that perceptual processes determine what parts of the visual field are attended to in the object-based models, with the caveat that most object-based theorists assume that perception is pre-attentive.

The attention-as-vision metaphor fares relatively well in the face of selected experimental data. There is evidence supporting the notion that saccades and attentional shifts share the same neural machinery (Sheliga, Riggio, & Rizzolati, 1994) and a number of studies suggest that attention serves as a targeting system ocular movements (Posner, 1992; Posner et al, 1988; Rafal & Robertson, 1995). On the other hand, research by Stelmach, Campsall & Herdman (1997) has shown that the attentional and vision systems can be dissociated to the extent that eye movements can be executed without a concomitant shift in attention. Furthermore, the notion that the focus of attention is a unitary phenomenon like the fovea has come under attack from experimental data, in particular from Driver and Baylis (1989). Despite these attacks the idea that perceptual processes and attention are very closely coupled and likely share many mechanisms is generally accepted and several papers suggest that perceptual grouping requires attention accepted (Mack et al., 1992; Rock et al., 1992; see also Ben-Av, Sagi, & Braun, 1992). Thus, while the mechanisms of attention might not map perfectly the ocular mechanisms, the notion that perception and attention can be cleanly separated, which has been traditionally assumed in the spatial and object-based models, is coming under strain. As discussed below, this will likely have an important effect on the object-based models of attention.

3. OBJECT-BASED ATTENTION

In the object-based attention approach, Gestalt grouping principles rather than spatial location are assumed to be the dominant factor in attentional allocation (Kramer & Jakobson, 1991; Lavie & Driver, 1996). This approach is based on research showing that information processing is facilitated when information is presented within a single object relative to when the same information is presented in different objects. Object-based models explain this by assuming that all elements belonging to a single object are attended in parallel whereas elements belonging to different objects are attended and processed serially. As noted below, an object-based approach can be accommodated in concert with spotlight models of attention.

3.1 Relating Object-Based Attention To Spotlight Models Of Attention

The spotlight metaphor has produced a number of models that make specific claims about the nature, medium and purpose of attention. In early spotlight models it was assumed that the information processed within the spotlight were simple features and spatial properties of the visual field. On this view, attention was necessary to integrate these features into objects. That is, attention was seen as part of the path from the processing of basic visual features to object identification and recognition. Recently, however, is has been hypothesized that the "content" of the spotlight are perceptual units or whole objects. Some researchers assume that the purpose of the spotlight is to select specific perceptual units for further processing (i.e. integration into a larger scene), whereas others (e.g. Tipper & Weaver, 1998), assume that attention enables a person to select specific objects within a scene in order to guide action. The former view of attention has come to be known as the spatial hypothesis of visual attention, whereas the latter is referred to as the object-based hypothesis attention.

It is important to note, however, that although object selection can be included into the spotlight metaphor, the metaphor is in fact more compatible with the spatial hypothesis. This is because the spotlight metaphor is usually taken to imply that attention is continuously (even if not uniformly) distributed within the spotlight, whereas the data favouring an object-based view suggests that attention is relatively discretely distributed between objects, and is not allotted to areas between objects. As noted by Fernandez-Duque and Johnson (1999), the metaphor which best fits the object-based view is "attention-as-spotlight-in-the-brain." To this end, the distinction between the different nature of the "objects" implicated in attention also serves to illustrate the fundamental difference between the spotlight and the spotlight-in-the-brain metaphors. Whereas the former is usually taken to imply that the role of attention is to integrate primitive perceptual units (features or objects) into more complex representations, the latter claims that the role of attention is not to enhance perception per se but rather to operate on the "output" of perception to direct action (decision-making and movement). Thus, the spotlight metaphor draws a tight link between attention and information processing, whereas the spotlight-in-the-brain metaphor draws a tight link between attention and action.

Importantly, there is nothing in the either the spotlight or the spotlight-in-the-brain metaphors that rule out the idea that "objects" of some sort (e.g. perceptual wholes that are more than mere features) are contents of the spotlight. Indeed, some investigators of object-based attention have noted that an attentional spotlight plays an important role in object-based attention (cf. Lavie & Driver, 1996). As noted by Yantis (1998, p.187), an attentional spotlight may be "responsible for selecting important or task-relevant objects for further detailed visual processing such as identification". However, other researchers have explicitly make the claim that attention selects representations of the environment, and not merely parts of the visual field, to control action (cf., Tipper & Weaver, 1998). Complicating matters, Yantis states that "perceptual organization mechanisms create object representations from the fragmented early visual image; visual attention selects one or more of these for delivery to high-level mechanisms" (Yantis 1998, p. 188). Thus, the correlation between object-based attention models and the spotlight-in-the-brain metaphor isn't so clear. Some proponents of object-based attention have models more in line with the simple spotlight metaphor, whereas others seem more inclined towards the spotlight-in-the-brain view.

3.2 Direct Experimental Support For The Object-Based View

Early support for object-based attention effects came from experiments reported by Duncan (1984) and Treisman et al. (1983). Duncan presented subjects with two overlapping objects, a box and a line drawn through it diagonally. The two objects could vary on two dimensions: the box could be small or large and have a gap in its right or its left edge; the line was either dotted or dashed (texture) or tilted to the left or to the right (orientation). The subjects' task was to identify the two attributes on either the line or the box or one attribute on each object. The results showed that subjects' identification was more accurate when the two attributes were located on a single object compared to when one attribute was located on one object and another attribute was located on the other object. According to spatial models, attention is directed to a location in space independently of any structure in the visual field. Given that the whole display was less than 1° of visual angle it would be hard for the space-based models to explain the same-object effect found in Duncan's experiment. On the other hand, the results are easily accounted for by the object-based hypothesis. When the two attributes to be identified belong to different objects, subjects must shift attention from one object to the other taking additional time and reducing accuracy.

Treisman et al. (1983) obtained a similar cost in performance when targets to be identified belonged to different objects. Subjects were presented with a rectangular frame and a word, which were configured in one of two ways. In one configuration, the frame and the word were presented apart (above and below a fixation point) representing two distinct objects. In the other, the word was presented within the frame, forming a single object. In both cases the distance between the outline of the frame and the word was 1° of visual angle. The subjects' task was to read the word and to judge the location of a gap in the frame. The gap was always located the same distance from the word. The Treisman et al. results were clear: performance was significantly facilitated when the word was presented within the frame (presumably forming a single perceptual object) compared to when the word and the frame were separate.

Both of these experiments strongly suggest that attention is allocated to perceptual objects in the visual field. Subsequent research has further supported this object-based claim. For example, Goldsmith (1998) showed that visual search is easier when features are linked to the same object than when they belong to different objects. Similarly, Duncan and Nimmo-Smith (1996) found that it is harder for subjects to discriminate between features that belong to different objects compared to a situation requiring discrimination between features that belong to a single object.

Driver and Baylis (1989) reported a groundbreaking experiment on object-based attention, which was based on evidence previously interpreted as strong support for a spatial attention hypothesis. This experiment examined response competition where interference of distractors on target response decreases in relation to increased spatial distance (Eriksen & Eriksen, 1974). Driver and Baylis used the Eriksen and Eriksen paradigm (subjects responded to a central letter located in an array of five letters) but grouped the target and distractors together using common motion. When the outer letters moved with the target they interfered more with target identification than the nearby letters that had remained stationary. This demonstrated how a seemingly spatial effect breaks down when the target and the distractors are grouped together. Using one of the Gestalt principles (common motion) the distant distractors were grouped with the target and as such produced more interference than distractors located closer to the target. The spatial models cannot account for these results, as the basic claim of the space-based hypothesis is that attention is allocated to contiguous regions in space, and that everything within such a region gets processed.

Baylis and Driver (1992) extended their work and showed that other grouping principles (than motion) can overwrite the spatial (proximity) effect. Subjects were required to respond to a central target (letter) while ignoring distractors located either near or far away from the target. In accord with the object-based attention hypothesis, when the distant distractors shared a colour with the target they interfered more with responses than distractors that were closer to the target. Also, as would be predicted based on Gestalt grouping principles, good continuation between the target and the distractors also resulted in more interference regardless of distance.

Kramer and Jacobson (1991) used a variation of the response competition paradigm (Eriksen & Eriksen, 1974) to test the object effect in a focused attention task. Subjects judged whether the target (a line) was dashed or dotted while ignoring distractors. Distracting lines (compatible or incompatible with target) were located to the left or right of the target. The distractors could be grouped according to the Gestalt principles with the target, or they could form a part of a different object. The distance between the target and the distractors was kept constant. According to the space-based models there should be no difference between the different conditions, as the spatial separation was constant. On the other hand, according to the object-based model there should be less interference when the distractors belong to a separate object. As predicted by the object-based model, the interference from distractors was indeed drastically reduced or eliminated when the distractors and the target belonged to different objects. Further, when the incompatible distractors formed part of the same object as the target, reaction time and accuracy was significantly reduced compared to when the compatible distractors belonged to the same object as the target.

In sum, it is quite apparent that the response competition that is produced by distractors as seen in the experiments mentioned above cannot be explained by referring to the spatial hypothesis. Grouping the distractors and the target together by colour or good continuation causes significantly more interference with target response than distractors that are easily separated from the target. Spatial distance seems to have no influence here. This suggests that visual attention is directed to perceptual objects in the visual field that are segmented according to the Gestalt grouping principles.

Experimental evidence supporting object-based attention has also been adduced from IOR tasks. IOR was originally interpreted as supporting spatial models of attention, as certain locations in space are prevented from being constantly re-examined. However, if attention is object-based then the inhibitory mechanism should be directed towards structure in the visual field rather than location. To this end, recent evidence suggests that IOR is related to perceptual objects in the visual field rather than spatial location (Tipper, Driver & Weaver, 1991). Jordan and Tipper (1998) used a static display to examine the difference between cueing location vs. cueing visible objects in the display. The display consisted of black "pacmen" (discs with a quadrant missing) and lines. In one condition objects formed by illusory contours (kaniza squares) were visible whereas in another condition no such objects were visible. The IOR effect was much larger when an object was cued compared to when only a location was cued.

3.3 Limitations In Experiments On The Object-Based Effect

Although there is a growing body of experimental evidence suggesting that visual attention interacts with perceptual grouping mechanisms, there are problems concerning the interpretation of these results. The main problem is that spatial proximity of elements in a display often correlates highly with those elements forming a perceptual whole (structure). Therefore data apparently supporting an object-based model can very often be interpreted according to a spatial model, and vice versa. What is needed is an experimental paradigm that allows for a clearer distinction between object-based and spatial effects.

A second, and related problem in studies attempting to differentiate between spatial and object-based models of attention is that often the whole display is so small that it is hard to rule out the possibility that any object effect might be happening within a larger, location based representation. For example, in Duncan's (1984) experiment the whole display was less than 1°; that obviously allows for only a very small and potentially insignificant variation in spatial distances. It could be argued therefore that object based factors are only important within an attentional spotlight. Similarly with the paradigm used by Treisman et al, (1983), the spatial area relevant when the word was presented within the frame was much smaller than the area relevant when the word and the frame were presented separately. Therefore Treisman et al.'s results might have reflected the benefit of closeness in space. Also the onset, of the frame may have exogenously grabbed attention making it difficult to read the word in the condition where the frame and word were presented separately.

Another problem in the literature is that the targets are often so different that the same-object effect can be the result of some artefact (e.g., spatial frequency differences). In Duncan's (1984) experiments, the two attributes of the line are available at a high spatial frequency whereas the two attributes of the box are available at low spatial frequency. The results may therefore reflect difficulties in processing or attending to different spatial frequencies. Furthermore, the targets used and the instructions given often indicate objects prior to the actual task. To wit, Duncan's procedure in which subjects were required to identify the height of a box and the texture of a line may bias subjects toward processing the stimuli as objects.

The aforementioned limitations highlight the need to (a) establish a better experimental paradigm that allows for a clear assessment of object-based attention effects and (b) acquire converging evidence for object-based attention from other research domains and

3.4 A Better Experimental Paradigm: Lavie And Driver (1996)

As noted above, many of the paradigms that have been used to examine the effects of object-based attention have generated results that are open to alternative explanations. One experimental paradigm that appears to provide a relatively pure index of object-based attention is that developed by Lavie and Driver (1996). Lavie and Driver's paradigm allowed for testing the difference between space and object-based models while avoiding many of the potential problems discussed above. Accordingly, the Lavie and Driver paradigm was used as a foundation for the present experiments.

The Lavie and Driver (1996) paradigm was designed based on four main criteria. The first criterion was to manipulate the division between the objects over a wide spatial area. This allows the examination of whether the object effect is only valid within a spatial "spotlight" and to measure both space and object-based effect at the same time. The second criterion was to make the target stimuli the same both within and between objects. This would rule out any possible artefacts such as spatial frequency differences etc. The third criterion was to create a task that was neither object dependent nor object independent. That is, the targets to be identified should form a natural part of the object without their identification in any way implying objectness. The final criterion was to keep eccentricity and acuity equal for all targets. Also, Lavie and Driver made sure that the instructions to the participants and the task requirements would in no way imply objects or location prior to the actual task performance.

The paradigm used by Lavie and Driver (1996) consisted of two dashed lines presented together briefly. One line was presented in green and the other one in red. Each line formed an object according to the principles of good continuation and grouping by colour. The whole display subtended 13° of visual angle. The subject's task was to respond as quickly as possible to targets that appeared on the lines. The two targets could either be a small dot replacing one of the dashes within a dashed line, or a gap (i.e. one of the dashes removed). Subjects responded by identifying (button push) whether the target were the same (two dots/two gaps) or different (a gap and a dot). There were three conditions, the near condition (the targets appeared close together in space but on different lines), the far condition (the target appeared far away in space and on different lines) and the object condition (the targets appeared far apart but on the same line). According to the spatial hypothesis the fastest response should occur under the near condition where the two targets are close together in space but located on different lines. There should also be no significant difference between the far and the object condition as the spatial separation in both cases is similar. On the other hand, according to the object-based hypothesis the fastest reaction time should occur within the object condition (far apart but on same line).

The results showed a clear object advantage thereby supporting the object hypothesis over the spatial hypothesis and establishing the paradigm as a valid tool for testing the object effect. Responses were significantly faster and more accurate under the object condition compared to the near and far condition. Furthermore, there was no significant difference in responses to the targets in the far and near conditions. The Lavie and Driver (1996) object effect seemed robust. Even when the proportion of the near trials (targets close together but on separate line) was doubled there was still a significant advantage for the object condition compared to the other two conditions. Similarly, equating the luminance of the lines and presenting the targets as either short of long white dashes had no impact on the object effect.

3.5 Converging Evidence: Neuropsychological Research On Object-Based Attention

Studies on patients suffering from neurological trauma (accidents, strokes, tumors etc.) provide information that further clarifies the interaction between perception and attention. In particular, these studies impact on the issue of the nature of the neural representations associated with attention. As summarized below, neuropsychological evidence strongly supports the notion that attention is object-based (Egly, Driver & Rafal, 1994; Humphreys & Riddoch, 1993; Robertson & Rafal, 2000).

The most common neurological condition implicating attention is unilateral neglect (Palmer, 1999; Humphreys & Riddoch, 1993). Unilateral neglect is due to a brain lesion in the parietal lobe, most commonly in the right hemisphere although lesions in the left hemisphere have also been reported to cause the disorder. Patients with parietal damage fail to notice stimuli that are located in the side of the visual field contralateral to the brain injury. For example, if asked to copy/draw a picture of an object (e.g., clock, ball, house), a patient with right parietal damage will draw only the right side of that object (Palmer, 1999).

Unilateral neglect has commonly been viewed as supporting space-based views of attention. However recent research shows that unilateral neglect is due to a difficulty in disengaging attention from a currently attended object within the unimpaired side to a new object within the impaired side (Humphreys & Riddoch, 1993; Kanwisher & Driver, 1992; Posner, et al 1987). For example, patients with unilateral neglect can often detect objects on <u>either</u> side of the visual field, when presented with objects on <u>both</u> sides simultaneously they only report the object on the side ipsilateral to the damage (Kanwisher & Driver, 1992). Further, when patients with unilateral neglect are asked to cross out lines drawn on a paper, only cross out the lines on the ipsilateral right side. However when asked to erase the lines, the patients will begin by erasing the lines on the ipsilateral side but will eventually erase the ones on the contralateral side as well. Since crossing out lines does not remove the lines from the visual field, it has been suggested that the patients are simply failing to disengage attention from the lines they just crossed out. On the other hand, when the lines are erased, it becomes easier to attend to the lines on the left as there are no longer any lines present on the right side to capture attention (Palmer, 1999).

Robertson and Rafal (2000) showed that if a patient with unilateral neglect is presented with a target and distractors, the location of the distractors (located on their unimpaired side versus both sides) affects target detection. If the distractors are only located on the unimpaired (ipsilateral) side, target detection decreases compared to the case where the distractors are located on both sides. It has been suggested that placing distractors only on the ipsilateral side to the target moves the center of the patient's representation of the display (the target and the distractors) further to the contralateral side in an object-based frame of reference. Hence the patient shows reduced accuracy and speed of performance. This finding is interesting as it suggests that performance is not related to spatial location in the visual field, but instead to where the object is located within an array of objects. That is, attention is based on grouped structures in the visual field rather than on spatial location.

Some of the strongest evidence that representations of objects influence attention comes from patients with Balint's syndrome (Humphreys & Riddoch, 1993; Palmer, 1999). Balint's patients cannot see anything except a single fixated object and it is extremely difficult for them to switch fixation from one object to another. Even in a complex field of many objects they fail to perceive more than a single object. This is even true when two objects occupy the same spatial location. For example, the patient can be looking at a person's face but fails to see that the person is wearing glasses. Also, when these patients are shown two objects overlapping in space (triangle and circle), they can only report one object. This is hard to account for with a spatial attention approach but fits well with the object-based attention hypothesis.

In an experiment by Humphreys and Riddoch (1993) two patients suffering from Balint's syndrome were presented with circles of different colours. The circles were either green or red and, the patient's task was to detect whether the circles had the same colour or whether they had different colours. There were three conditions, random, single-object and mixed-object. In the random condition black lines were placed randomly in between the coloured circles. In the single-object condition, the same black lines connected circles of same colour together, thereby forming a single object. In the mixed-object condition, the lines connected circles of different colour together similarly forming a single object. All three conditions had circles of green and red colours located close together, the difference being the colour of the circles, which were connected. The spatial separation between the circles varied. The results showed that the patients had better performance in the mixed condition compared to single-object or random conditions. If attentional capture is space-based then there should not have been any difference between the random and mixed-object conditions. In the random condition circles of different colours were located closed together, although not connected as in the mixed-object condition. On the other hand, if attentional capture is object-based, as has been suggested, the mixed-object condition should be helpful, since fixating on a single object (circles of different colours connected) in this case gives the patients all the relevant information for identifying whether the circles are the same or not. In the random condition the patients would fixate on a single circle, making it difficult to attend to other circles in the display. Similarly, in the single-object condition, attending to a single object (where only circles of the same colour are connected together) doesn't help the patients compare the colour of the circles in the display. A further problem for spatial models is that variation in spatial distance did not change the benefit found for the mixed-object condition.

Further evidence that attention is object-based is found in electrophysiological studies measuring event-related potentials (ERPs). Valdes-Sosa, Bobes, Rodriguez and Pinilla (1998) measured ERPs with a paradigm designed to test object-based effects. Subjects were presented with two sets of dots that differed in colour. The subjects were instructed to attend to either set of dots (green or red). Their task was then to detect a brief linear displacement within one set of dots and detect the dominant direction of movement (only a subset of dots moved in the same direction). The sudden onset of the linear displacement served to elicit motion onset ERPs. In one condition, the two sets of dots rotated in opposite directions creating the perception of two transparent surfaces sliding across each other. In another condition the two sets of dot remained stationary, creating the percept of a single object. In a third condition, the two sets of dots rotated in the same direction similarly creating the percept of a single object. The results showed a clear difference between the dual-object and single-object conditions. In the dual-object condition there was a large difference in ERP depending on whether the linear displacement occurred in the attended or unattended set of dots. In particular, whereas a clear ERP was found when the linear displacement occurred in the attended set, a strong suppression was found for all components related to ERP when the linear displacement occurred in the unattended object. No difference between the attended and unattended sets was found in the single object condition.

Studies on the neurological basis of attention suggest the existence of two components to the object-based control of attention. On the one hand, attention is directed to whole perceptual groups in space. On the other hand, evidence strongly suggests that there exists a coordinate system that allocates attention within more spatial invariant object-centered frame (Behrmann & Tipper 1994; Reuter-Lorenz, Drain &

Hardy-Morais, 1996). An object-centered frame does not change according to position in the visual field or viewer perspectives. Research, on patients with unilateral neglect supports the idea of object-centered frame: Patients with unilateral neglect will often neglect one side of the object (contralateral to the damage) regardless of the position of the object in the patients' visual field. For example, if a person stands in front of a neglect patient, the patient will not see the person's right arm (the arm on the patient's left side). However, if the person rotates 90° to the left or right, the patients still fails to see the right arm, regardless of the fact that when rotating to the left the right arm will fall within the patients unimpaired visual area (Robertson & Rafal, 2000). Furthermore, if an object is placed entirely within the unimpaired field of vision, patients with unilateral neglect still do not perceive an aspect of the object on the side contralateral to the lesion. This suggests a frame of attentional control that is determined by a single object (Palmer, 1999; Reuter-Lorenz et al, 1996).

Although most evidence, suggesting an object-centered frame of attentional control comes from patients suffering from brain lesions, there is evidence suggesting that it also influences the normal brain. As noted by Reuter-Lorenz et al. (1996), subjects with normal brain function show a contralateral attentional bias for each hemisphere. That is, detecting a target located on the left side of an object in the left visual field is easier than if the target is on the right side. The same benefit is found for right side with objects in the right visual field. As with the data from unilateral neglect patients, this hemispheric data shows that attention is allocated on the basis of object-based representations of the environment in non-patient populations.

3.6 Object-Based Attention To Moving Stimuli

Most investigations of object-based attention have involved the use of static or near-static displays. However, insofar as HUDs are used in dynamic visual environments, research examining how attention is assigned to moving objects is clearly relevant.

Pylyshyn and Storm (1988) tested the assumption, arising from a spatial model of attention, that people are able to track many elements by moving their attentional spotlight from element to element in rapid succession. They first tested subjects' ability to track independently moving and similar elements within a display of many moving elements. This showed that people are able to successfully track about four or five elements for at least 10 seconds. A computer simulation of this task was developed using the actual trajectories that were shown to subjects combined with a model of a spatial spotlight. This simulation showed that an attentional spotlight moving from element to element would not be able to keep track of the elements. Thus, Pylyshyn and Storm concluded that a spatial attention hypothesis can not account for people's ability to perform multiple object tracking.

There are two object-based accounts of how people might perform multiple tracking of objects. One account is that the multiple elements are formed into a nonrigid polygon, with each element being one of the vertices of the polygon. On this view, Yantis (1992) found that tracking performance is affected by factors that facilitate the initial formation and maintenance of a perceptual group of elements to be tracked. Thus, Yantis argues that specific elements within a display of similar moving elements are tracked by grouping the elements into a single "superobject" (essentially a nonrigid polygon). The less polygon-like the nonrigid polygon is, the harder the task.

Pylyshyn and his colleagues have developed a different account, which assumes that each element being tracked is associated to a visual index, or a FInger of INSTantiation (Pylyshyn, 1989). On this view, the early visual system attaches indexes to the individual elements to be tracked. These indexes provide a way for the visual system to pick out specific elements of the visual field by referring to the elements themselves, and not to any properties of the objects (Pylyshyn, 1998). These indexes then allow the rest of the visual system to attend to those specific elements, to track them, to identify them, and so on (Scholl & Pylyshyn, 1999; Sears & Pylyshyn, in press). Thus, visual indexes are a kind of representation or data structure within the visual system which function in a manner analogous to linguistic indexes and demonstratives (e.g. words such as "that" or "there").

In sum, the ability to track moving objects appears to require that attention be object-based at least to some degree. Spatial models of attention are inadequate for explaining the experimental evidence obtained from multiple tracking tasks, as these models would require the spatial spotlight to visit each moving element in rapid succession. Successive tracking of this sort would mean that the visual system is able to predict the positions of the moving elements and to move the attentional spotlight at a speed that are beyond the capacities of the human visual system.

3.7 Summary

A growing body of experimental and neuropsychological research supports the conclusion that attention is referenced to perceptual groups or objects within the visual field. This is known as the object-based attention hypothesis. The object-based attention hypothesis provides an account of attentional effects in both static displays and in situations where objects must be tracked.

The object-based attention hypothesis has implications for research and development of HUDs and for the integration of HUDs into HMDs. For example, based on Gestalt principles, perceptual groupings of HUD symbology will be formed based on common motion, colour, proximity, closure and/or figure-ground separation. Object-based attention may underlie difficulties associated with pilots' need to process near (HUD) and far (external scene) domain information: near and far domains differ along one or more of the Gestalt grouping principles. An object-based attention framework, and a corresponding paradigm for assessing object-based attention effects, would be useful for gaining a metric on near versus far domain attentional capture and cognitive tunnelling. Such a paradigm would also provide a method for measuring the impact of conformal vs. nonconformal symbology.

SECTION TWO: EXPERIMENTS ON OBJECT-BASED ATTENTION

There is a growing body of experimental and neuropsychological research supporting an object-based attention hypothesis where attention is assumed to be allocated to objects in the visual field (Duncan, 1984; Kanwisher & Driver, 1992; Kramer & Jacobson, 1991; Humphreys & Riddoch, 1993; Valdes-Sosa, et al. 1998). Research within the field of aviation psychology has adopted the object-based attention hypothesis in order to explain cognitive tunnelling and other perceptual/attentional problems in HUDs. Indeed, as noted in Section One of this report, a review of the literature shows that the object-based attention hypothesis provides a promising framework for the systematic study of the attentional problems associated with HUDs. However, the use of the object-based attention framework in the aviation literature has been based on loosely defined concepts and a lack of understanding of how the object-based hypothesis may apply to the dynamic environment of HUDs. For example, one of the misconceptions is that the only relevant "objects" of concern for attentional control are the near (HUD) and far (external scene) domains. As noted in Section I, forming coherent objects within a single domain can have important perceptual/attentional consequences. Furthermore, the vague object-based attention framework that exists in the aviation literature makes it difficult for researchers to avoid confounding object-based effects with other factors that may influence performance.

The goal of the present research program was to further develop the object-based attention framework for HUD/HMD applications. A series of five experiments are reported in this section. Experiments 1 - 4 were conducted to (a) establish an object-based attention paradigm: to obtain a sense of effect sizes and reliability, impact of instructional sets, and laboratory constraints, (b) obtain initial evidence regarding what attributes are necessary in order to make an object, and (c) examine the relationship between object-based attention and spatial cueing. The Lavie and Driver (1996) experimental paradigm was used as a foundation for the present experiments. In Experiment 5, the object-based attention paradigm was extended to a dynamic display.

Experiment 5 represents a significant step toward achieving the goal of examining object-based attention effects in HUDs and HMDs.

EXPERIMENT 1

Establishing An Object-Based Attention Paradigm

The goal of Experiment 1 was to establish an initial experimental paradigm to examine effects of object-based attention. To do this, the paradigm developed by Lavie and Driver (1996) was adopted. This paradigm allows for the simultaneous manipulation and/or control of spatial separation while examining object factors. In addition, the Lavie and Driver paradigm addresses earlier criticisms on studies comparing object and space-based effects on attention. The display extends over a large spatial area of roughly 14°. The targets used are the same for all conditions and they are equally located from central fixation point. Instructions and task requirements gave no prior indication of objectness.

The display consisted of two dashed lines. Subjects' task was to identify whether two targets (a dot and a gap) appearing anywhere in the display were the same or different. The targets appeared far apart on either the same line (object condition), far apart but on different lines (far condition), or they appeared close together on different lines (near condition). According to the spatial hypothesis, latencies should be lower in the near than far condition because the spatial separation of the targets is less in the former condition. The spatial hypothesis also predicts that latencies should be generally equivalent in the same in the object as in the far condition. If any differences are found, latencies should be faster in the far than the object condition because the spatial separation of targets is slightly larger in the object condition.

The object-based attention hypothesis states that it is faster to search for targets on a single object (one line) than targets presented on two different objects (two lines) (Duncan 1984; Kramer & Jacobson, 1991). Accordingly, the object-based prediction is that responses should be faster in the object than the far condition. Faster responses to targets in the object than the near condition would represent strong evidence for an object effect. This pattern would show an effect of object-based attention that transcends differences in spatial separation: targets are much closer in the near than the object condition.

Method

Subjects. A total of 7 university students participated in the study. Two of the subjects were aware of the hypothesis in the study.

Apparatus. The stimuli were presented using an IBM-compatible 486 computer and a 14 inch VGA colour monitor. Responses were recorded using the numeric keypad on the computer's keyboard. The experiments were created and run using Micro Experimental Laboratory (MEL) version 2.0 (Schneider, 1995). Response times were accurate to 1 ms.

Stimuli. The stimuli were one red dashed line and one green dashed line presented against a grey background. The lines intersected at their midpoint at the centre of the display. One line was horizontal and the other line was tilted at an angle of 18°. Each dashed line was equally likely to be red or green. The horizontal line was 18.9 cm long and the tilted line was 20.2 cm. At a fixed viewing distance of 80 cm the whole display extended slightly over 14° of visual angle. Each line contained 15 elements equally spaced. The dashes were 0.9 cm in length and two pixels in height.

For each trial two of the dashes were replaced with the targets, a dot and a gap. The dot was placed at the centre of the dash it replaced and the gap element was made by eliminating one of the dashes. The targets (dot or gap) were located toward the periphery of the display as the third or fourth dash from the end of each line. Within each trial one target was placed as the third element from one end and the other target was then placed as the fourth element from the other end. This was to avoid any unintended symmetries or subjective contours that might arise between the target elements in some conditions. Targets were equally likely to appear as the third or fourth element on the horizontal or tilted line and the two targets were equally likely to appear in the horizontal and the tilted line. On half of the trials the targets were the same and on the other half different. When the target were the same they were equally likely to be two dots or two gaps. Finally the targets were equally likely to occur within any of the three conditions (near, object, far). The distance between the target elements (measured between their centres for convenience) was 1.4° or 1.7° in the near condition, depending on the precise location of the targets in the display, 8.8° in the object condition and 8.4° in the far condition. A total of 96 different displays were constructed to account for all the possible variations.

Procedure. Subjects viewed the screen in a darkened room with their head stabilized in a chinrest. Each trial began with a fixation point displayed at the centre of the screen for 1 second. Following the fixation point, the lines appeared simultaneously for 177 mss; the brief presentation of the lines prevented the subjects from physically scanning the display. Subjects were required to make a speeded judgement of whether the targets were the same (two dots or two gaps) or different (a dot and a gap) using the numeric keypad on the keyboard. Subjects pressed "0" for *same* and "2" for *different*. Error feedback was given immediately by the presentation of a 500 ms computer tone.

Subjects were explicitly instructed that the target would appear towards the periphery of the display in any possible combination. The displays were presented in random intermixed order in blocks of 64 trials. After each block the subject was given the opportunity to rest before starting the next block. There were 11 blocks, 1 practice plus 10 experimental for a total of 640 experimental trials.

Results

Mean reaction times on correct trials for the six experimental conditions are given in Figure 1.[1] It is clear from the figure that the *object* condition (for both *same* and *different* responses) had the lowest latencies. The latencies were analyzed with a 2(target: same vs. different) x 3(condition: *near, object, far)* ANOVA with repeated measures on all factors. There was a significant main effect of condition, $F(2,12) = 6.295$, $MSE = 1594.139$, $p < 0.05$. A comparison of the *object* and *far* conditions using a 2(target: same vs. different) x 2(condition: *object* vs. *far*) ANOVA also showed a significant effect of condition, $F(1,6) = 7.772$, $MSE = 1642.985$, $p < 0.05$, as did a 2 x 2 ANOVA comparing the *object* and *near* conditions, $F(1,6) = 6.441$, $MSE = 2644.173$, $p < 0.05$.

Discussion

In sum, subjects were fastest to respond in the *object* condition. This is consistent with the object-based hypothesis that attention is assigned to features that are grouped into objects based on Gestalt grouping principles. One implication of this result for HUD design is that attention will be assigned to elements in a symbology set that form coherent objects or perceptual groups. This could potentially have very important design implication both for the form of individual symbols and for the use of grouped symbols in HUDs.

[1] Throughout the experiments reported in this section, the primary analyses focused on latencies. Error rates were generally uninformative and are thus not discussed.

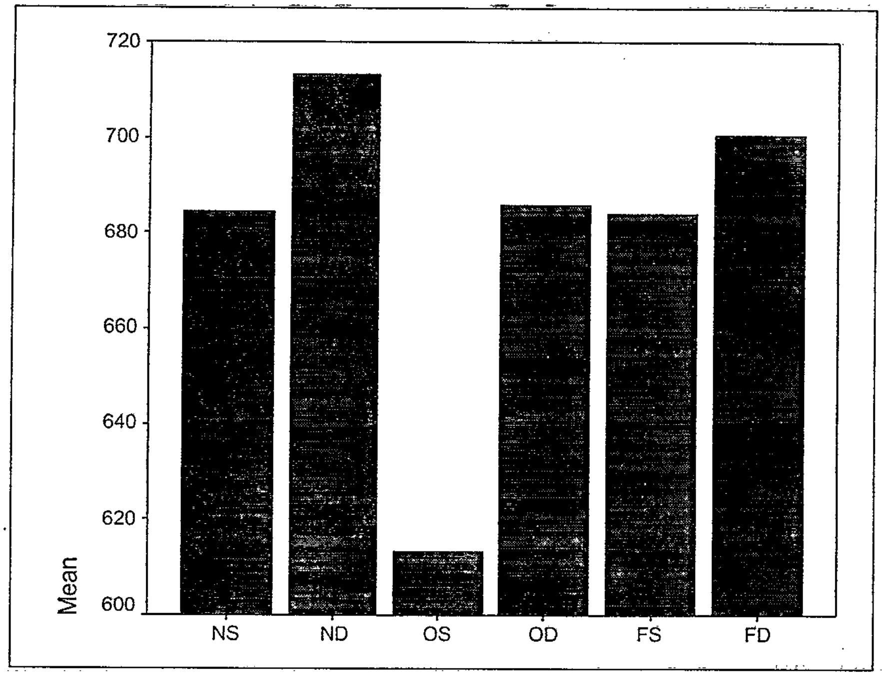

Figure 1. Mean reaction times by condition for Experiment 1. NS: near same; ND: near different; OS: object same; OD: object different; FS: far same; FD: far different

EXPERIMENT 2

Object Effects and Spatial Cueing

An important aspect of the overall safety for pilots using HUD is the presence of clear and effective warning signals. Research has shown that the sudden onset of a stimulus serves as an effective exogenous cue for drawing attention to a particular location (Posner, 1980; Stelmach & Herdman, 1991; Wright & Ward, 1998). In HUDs, such cues may be instantiated as transient or flashing symbols.

When dealing with a of multitude of information in both the near and far domains, a warning signal has to effectively capture pilots' attention away from any other sources of information. As the problem of cognitive tunnelling demonstrates, the presence of perceptual groups and coherent objects in the symbology might capture attention to the point of hindering pilots' detection of, and responses to the warning signals. It is also possible that effective warning cues might disrupt the processing of perceptual groups in the symbology in unforeseen ways.

The purpose of Experiment 2 was to examine the interaction between object-based attention and exogenous cueing. This was done by adding an exogenous spatial cue to the object-based attention paradigm used in Experiment 1.

Method

Subjects. A total of 24 undergraduate students participated in this study. The students received partial course credit for participating in this study.

Apparatus and Stimuli. The apparatus was the same as in Experiment 1. The stimuli were similar to those used in Experiment 1, with the following exceptions. Instead of using red and green as line colours, one line was presented in pink and the other in yellow. The two lines (horizontal and tilted) were equally likely to be yellow or pink. The targets were a white dot or a white dash (same length as the non-target dashes)[2].

Procedure. Stimuli (the dashed lines and the targets) were presented for 130 ms rather than for the 177 ms used in Experiment 1. The lines were preceded by spatial cues that appeared for 66 ms on either the left or the right side of the display (ISI of 0 ms). The spatial cues consisted of the endmost dash of both lines. The early onset of the spatial cues was presumed to draw subjects' attention to the cued side of the display. The interval between the onset of the cue to the offset of the display was brief, thereby preventing overt attentional or ocular shifts.

The cue was valid on 70% of the trials. That is, on 70% of the total trials the cue was followed by the occurrence of the targets in the near condition (close together on separate lines) on the side of the cue (*valid-near*). The remaining trials were equally likely to occur within the near condition on the side opposite to the cue (*invalid-near*) or within the object condition (*invalid-object*) or far condition (*invalid-far*).

As in Experiment 1, the targets were the same or different equally often for each of the conditions. Each block consisted of 80 trials, 8 displays from each of the invalid conditions and 56 displays from the valid near condition on average. The cue was equally likely to appear on left or right side. Subjects started with a short block of 12 demonstration trials followed by 11 blocks of 80 trials each. The subjects were explicitly instructed to pay close attention to the cue since the targets would appear most often on the cued side.

[2] The use of these colours was prompted by concerns over the possible effects of line colour on target discrimination.

Results

Subjects' mean reaction times for correct trials were computed for the eight experimental conditions (factorial combination of the four target location conditions and the two target length conditions) and are shown in Figure 2. The latencies were analyzed with a 4(condition: *near-valid, near-invalid, object-invalid, far-invalid*) x 2(target: same vs. different) repeated-measures ANOVA. The analysis showed that the main effect of condition, $F(3,69) = 9.758$, $MSE = 3543.196$, $p < .001$, was significant. A comparison of the *near-valid* and *near-invalid* conditions with a 2(condition) x 2(target) ANOVA also showed a significant effect of condition, $F(1,23) = 20.324$, $MSE = 3189.147$, $p < .001$, as did comparisons of the *near-valid* and *object-invalid* conditions, $F(1,23) = 11.394$, $MSE = 2775.934$, $p < .005$, the *near-invalid* and *far-invalid* conditions, $F(1,23) = 21.139$, $MSE = 4200.791$, $p < .001$, and of the *object-invalid* and *far-invalid* conditions, $F(1,23) = 5.566$, $MSE = 2593.916$, $p < .05$. Taken together, these results show that the latencies for the *near-valid* condition are significantly lower than for the *near-invalid, object-invalid* and *far-invalid* conditions; and that the *object-invalid* trials were reliably faster than the *far-invalid* trials.

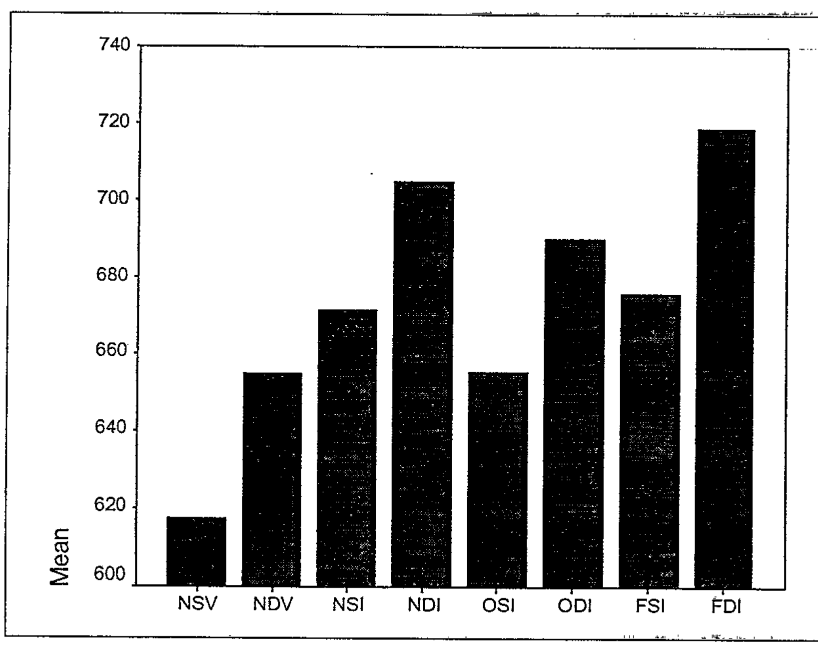

Figure 2. Mean reaction times for Experiment 2. NSV: near-valid, same; NDV: near-valid, different; NSI: near-invalid, same; NDI: near-invalid, different; OSI: object-invalid, same; ODI: object-invalid, different; FSI: far-invalid, same; FDI: far-invalid, different.

In sum, the main result of this experiment is that the cueing of one side of the display had a significant impact on the pattern of reaction times as a function of condition that was found in Experiment 1. Unlike the result from the Experiment 1, which showed faster responses in the *object* condition, the lower latencies for this experiment were found for the *near-invalid* conditions. The slowest responses were found in the *far-invalid* conditions. These results show that spatial cueing eliminated the effects of object-based attention.

Discussion

This experiment suggests that attentional capture by the use of spatial cueing can have potentially disruptive effects on the mechanisms involved in object-based attention. The spatial cues clearly facilitated responses to both types of *near* targets (valid and invalid), to the extent that the advantage displayed for the *object* condition found in Experiment 1 was eliminated. Another significant outcome of this experiment is that the perceptual grouping of the dashes into longer lines, presumably the basis for the object effects observed in Experiment 1, did not prevent the cueing from being effective. This suggests that the grouping principles which possibly account for object-based attention do not interfere with spatial cueing to a large degree, at least not when the cues and the perceptual groups overlap spatially (note, however, the experiments on cognitive tunelling suggest otherwise for cues and objects that do not directly overlap, be they in the near or far domains; see Fischer, Haines & Price, 1980; McCann & Foyle, 1996; Wickens & Long, 1994).

What is the basis for this effect of cueing on object-based attention? In an experiment using the same paradigm, Lavie and Driver (1996) found relative ranking of the latencies according to condition as follows: *near-valid, near-invalid, object-invalid, far-invalid.* On its own, this ranking is suggestive of spatial effects typically associated with spatial cueing (see Posner, 1980). Spatial cueing might momentarily disrupt mechanisms of object-based attention by changing the size of subjects' attentional "spotlight," in line with the zoom-lens account of Eriksen and colleagues (Eriksen & Eriksen, 1974; Eriksen & St-James, 1986). The premise in this argument is presumably that the mechanisms of object-based attention can only operate in a stable attentional spotlight, thus implying some sort of hierarchical relationship between spatial and object-based attentional operators.

However, the evidence for this account is far from conclusive. Examination of the invalid trials in this experiment shows that the lowest latencies were found for the *object-invalid* condition, followed in order by the *near-invalid* and *far-invalid* conditions. The difference in latencies was not found to be significant, except in the case of the *far-invalid* condition when compared to the *object-invalid* condition. If further research were to confirm the findings of this experiment, then it could be argued that spatial cueing of a region of a display facilitates responses to events in that region, without necessarily disrupting the effectiveness of object-based attentional operators. Furthermore, the findings related to cognitive tunelling suggest that spatial cueing might have a differential impact on the processing of perceptual groups depending on whether the cues and the perceptual groups overlap in space. Further research is clearly needed on this important issue.

The apparent contrast between these present results and those reported in experiments on cognitive tunnelling also suggest that the degree to which a cue is expected and/or predictable could be a factor in determining its effectiveness. In the studies reported by Fischer, Haines and Price (1980) and Wickens and Long (1994), the events that failed to be noticed, or were reacted to more slowly, by pilots were often (but not always) unexpected and were generally presented on a limited number of trials. The cues used in this experiment were fully expected to occur at the onset of each trial by the subjects. Moreover, the cues used in this experiment were highly informative, in that they predicted the location of targets with 70% accuracy, which provided even more incentive to attend to them. Could subjects' expectation that the cue was going to appear and their intention to seek out and use the target to aid their performance have been a factor in the effectiveness of the cues? This is the question considered in Experiment 3.

EXPERIMENT 3

Explicitness of the Spatial Cueing

Experiment 3 was conducted to further explore the impact of spatial cueing on object-based attention. Two changes were made from Experiment 2. First, in Experiment 2, spatial cues were presented for only 66 ms; research has shown, however, that exogenous cueing is most effective at around 100 ms (Wright & Ward, 1998). In this experiment, some subject saw a display where a 99 ms cueing interval was created by presenting cues for 66 ms followed by a 33 ms blanking interval before the onset of stimuli. Second, in Experiment 2 subjects were explicitly instructed to use the spatial cues. In the present experiment, subjects were given no explicit instructions to use the cues and the cue validity was not made explicit; in fact, no mention at all was made of the presence of the cues. The purpose of these changes was twofold: the omission of information about the cues from the instructions to subjects was aimed at examining the effects of subjects' expectations about the cueing on cue effectiveness; the use of an exogenous cue with proven effectiveness was meant to provide a baseline to compare the effects of expected cueing (Experiment 2) and the unexpected cueing of this experiment against.

Method

Subjects. A group of 20 first-year undergraduate psychology students participated in this study. The students received partial course credit for their participation. None of the students had participated in the previous experiments.

Apparatus, Stimuli and Procedure. The apparatus, and stimuli were the same as in Experiment 2 with the difference noted earlier: one group of subjects (N = 11) saw displays with the same cues as were used in the previous experiment, whereas the other group (N = 9) was shown displays using the longer cueing interval. The procedure was the same as for Experiment 2, with the difference that the subjects in both groups were given no information about the presence or usefulness of the cues.

Results

The mean reaction times for each experimental condition (*near-valid, near-invalid, object-invalid, far-invalid*) were computed for correct trials. Figure 3 shows latencies as a function of cue type (short cue: panel a; long cue: panel b). These latencies were analyzed with a repeated-measures 4(condition) x 2(target: same or different) ANOVA, with type of cue as a between-subjects factor. The ANOVA showed a significant main effect of condition, $F(3,54) = 5.206$, $MSE = 5383.134$, $p < .005$. A comparison of the *near-valid* and *near-invalid* conditions with a 2(condition) x 2(target) ANOVA with cue as a between-subjects factor also showed a main effect of condition, $F(1,18) = 6.898$, $MSE = 2974.819$, $p < .05$, that was significant. No other 2 x 2 comparisons between conditions revealed significant effects. The between-subjects effect of cue type failed to reach significance in all analyses.

In sum, the main result of this experiment is that responses were fastest for the *near-valid* and *near-invalid* conditions, with *near-valid* being significantly faster than even *near-invalid*. This is generally consistent with the findings of Experiment 2, and with the findings of Lavie and Driver (1996). It should be also noted that the between-subjects factor of cueing length was only implicated in one interaction. Thus, these results show that the length of the cueing interval used in this experiment had little impact on subject performance.

Discussion

The results of this experiment suggest very strongly that subjects expectations about the occurrence and usefulness of cueing has little impact on the results of Experiment 2. If fact, many subjects denied seeing the cues at all, although the overwhelming majority did report perceiving the lines as being drawn from a given side of the display, an effect which was also reported in Experiment 2, but which did not occur in Experiment 1 where no spatial cues were used. Clearly, the cues did have a phenomenological impact on the perception of the display, seemingly generating an apparent motion effect. At any rate, it would seem that the spatial cues can be effective in capturing attention in a display of grouped elements without observers expecting them or

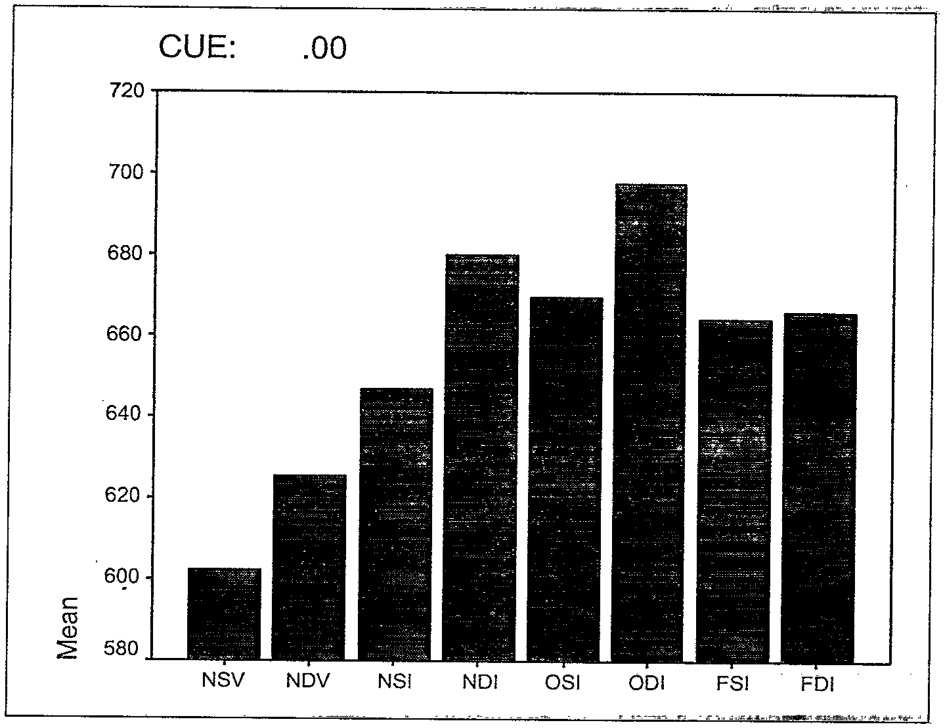

Figure 3a. Mean reaction times for Experiment 3, short cue condition (N = 9).

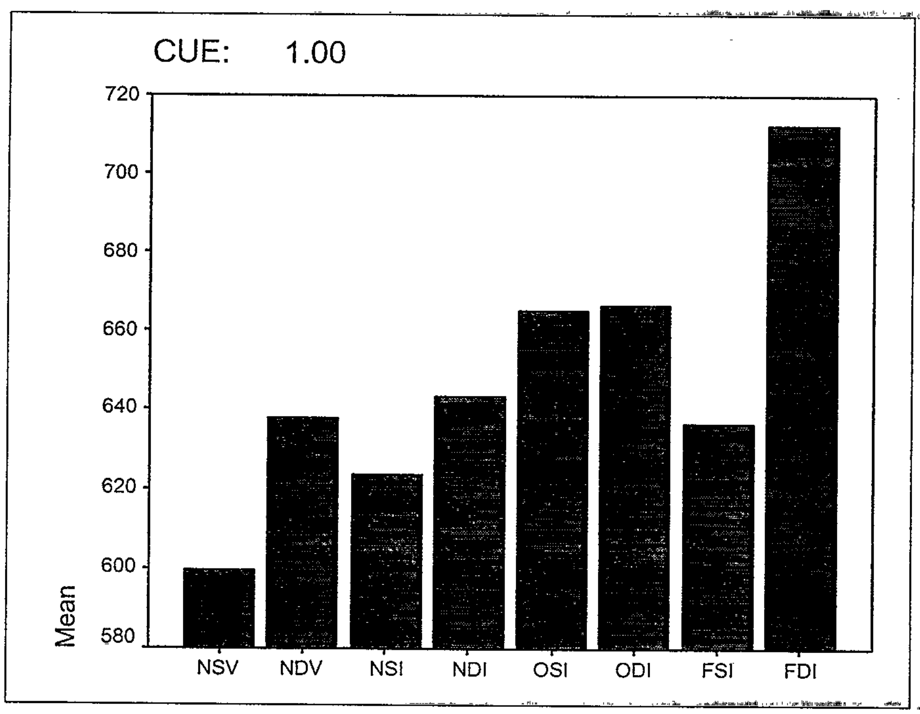

Figure 3b. Mean reaction times for Experiment 3, long cue condition (N = 11)

intending to use them, or even being phenomenologically aware of them as cues.

The similarity between the reaction times for the *object-invalid* condition and both types of *near* condition, and the significant difference between the *object* and *far* invalid conditions observed in Experiment 2 were absent in the case of this experiment. It is unclear whether this is due to the differences in cueing between Experiments 2 and 3, as the number of subjects per cueing condition in Experiment 3 was too low to produce reliable effects.

EXPERIMENT 4

Is Colour Necessary To Form An Object?

Experiment 1 showed a strong effect of object-based attention with objects (lines) that were defined by two Gestalt grouping principles: good continuation and colour. It is not clear, however, whether both of these attributes were required to create two separate objects. In systems such as NVGs, the HUD symbology is monochromatic. If colour differentiation is critical for creating perceptual objects, then designing HUD symbologies meant to exploit the attentional benefits of objects and perceptual grouping may be problematic in cases where the HUD must be monochromatic or is restricted to a very limited colour palette. Experiment 4 was designed to make some headway on this issue by using the displays and procedures of Experiment 1, with the difference that the stimuli of Experiment 4 are monochromatic. Thus, the objects (lines) were defined only by the principle of good continuation.

Method

Subjects. A total of 10 first-year undergraduate psychology students participated in this study. The students received partial course credit for their participation. None of the students had participated in the previous experiments.

Apparatus, Stimuli and Procedure. The apparatus, stimuli and procedure were the same as in Experiment 1 with the exception that the stimuli (the dashed lines and the target consisting of a dot) were presented in black on a light grey background. The second target was a gap (a missing dash), as in Experiment 1.

Results

The mean latencies for the six experimental conditions on correct trials are reported in figure 4. Data from three subjects with performance approaching chance was discarded. The means were analyzed with a 3(condition: *near, object, far*) x 2(target: same vs. different) repeated-measures ANOVA. The analysis showed an effect of condition, $F(2,12) = 5.044$, $MSE = 560.577$, $p < .05$, which was significant.

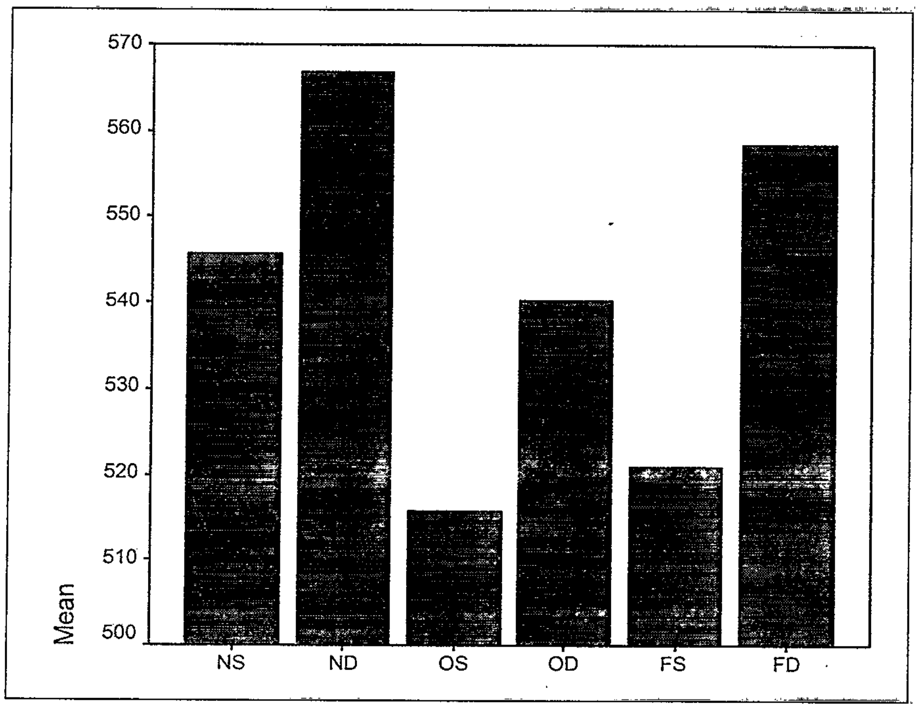

Figure 4. Mean reaction times for Experiment 4.

A comparison of the *near* and *object* conditions with a 2(condition) x 2(target) ANOVA revealed a significant effect of condition, $F(1,6) = 8.482$, $MSE = 660.520$, $p < .05$. No other effect achieved significance, although the effect of condition approached significance in a comparison of the *object* and *far* conditions, $F(1,6) = 4.038$, $MSE = 240.207$, $p < .1$.

The main result of this experiment is that the *object* condition produced the lowest mean latencies for the three conditions. This replicates the results of Experiment 1 and is consistent with the object-based hypothesis.

Discussion

The results of this experiment show that colour is not a necessary feature for perceptual grouping. This has important implications for HUDs with systems that offer only monochromatic symbologies (e.g., NVGs), in that such systems should still support the allocation of attention in an object-based manner, thereby allowing the design of these symbologies to exploit the insights gained from research on object-based attention as well.

However, this is not to say that colour plays no role in perceptual grouping. A comparison of Figures 1 and 4 (colour & no colour) shows that the effect of objectness was smaller in Experiment 4 than in Experiment 1, by about 20 ms. Furthermore, there is a suggestive trend towards trials in the *far* condition being faster than in the *near* condition. This could conceivably be due to the display being grouped into a single, large object (i.e. a tilted 'X') in the *far* condition, while failing to do so in the *near* condition, perhaps because not enough of the display is being attended to in order for grouping into a single object to occur in the latter case. If these results are borne out by further research, it could suggest a role for colour as an adjunctive grouping factor, strengthening certain groupings primarily determined by symbol geometry. These same results also suggest the idea that perceptual grouping might be a hierarchical process, wherein certain objects are the result of the grouping of other, simpler objects. If this is true, the design of HUDs could benefit from the hierarchical nesting of symbols to facilitate the integration of information within the symbology and to deal with issues such as visual clutter and attentional capture.

SUMMARY OF EXPERIMENTS 1 - 4

Experiments 1 - 4 have been important in establishing an object-based attention paradigm which is reliable and which allows for the systematic study of a variety of factors which might interact with object-based attention. One set of factors which can be explored with this paradigm are spatial factors. Initial steps have been taken toward examining the relation between object-based attention and spatial cueing (Experiments 2 & 3). This is particularly relevant to the development of a framework for designing and testing warning signals for HUDs in a principled manner. Another set of factors that can be manipulated in this paradigm are the factors which determine the grouping of elements into coherent wholes or objects. One such factor that was investigated was colour (Experiment 4). The results of this study suggest that colour does not play a primary role in perceptual grouping, although it might well play an ancillary role. This is good news for the design of HUDs for systems such as NVGs which require monochromatic symbology.

Experiments 1 - 4 raise a number of questions. One such question has to do with the exact nature of the interaction between spatial cueing and object-based attention. Another concerns the role of hierarchical perceptual grouping in attention. Finally, as these experiments do not address issues, which might arise from the use of symbology in dynamic displays, including the use of symbology which itself is dynamic.

It is known that common motion is a very powerful grouping factor, as has been revealed by work on the development of object perception (Spelke, Gutheil & Van de Walle, 1995) and further supported by experimental work in cognitive neuroscience (Valdes-Sosa, Cobo & Pinilla, 1998). In the area of HUD design, recent HUD prototypes, such as the Technical Panel Two (TP2) symbology set, segregate groups of related symbols by the use of common motion. Can the grouping of elements, which can be perceived and attended to as objects in their own right, lead to attention being allocated to the group as if it were an object itself? If so, will this be of use in addressing the problems of integrating information both within a domain and across domains?

EXPERIMENT 5

Object-Based Attentional Layers in a Dynamic Display

In aircraft, stimuli in both the near (HUD) and the far (external scene) domains move. This dynamic visual context differs from the static displays that have been used by researchers to examine object-based attention. Accordingly, the purpose of Experiment 5 was to translate the object-based attention paradigm used in Experiments 1

- 4 to a situation where elements on the display are moving. Experiment 5 was not intended to fully mimic a complex HUD-equipped aircraft environment, but instead, to take a logical and significant step forward.

This experiment makes two significant contributions. First, this experiment demonstrates a capability in the development of a paradigm that can be used to assess object-based attention in a dynamic context. This capability will enable future research on object-based attention in HUD displays. Second, this experiment is the first to show that object-layers are formed through common motion and that these object-layers can be attended.

In the current paradigm, subjects were presented with a number of dots on a display. A subset of these dots moved in unison (common motion) while the other dots remained stationary. It is known that common fate (or common motion) is one, if not the strongest of the perceptual grouping factors (Spelke et al., 1995). The moving dots formed what is termed a moving layer. The stationary dots formed a static layer. The creation of these two layers is analogous to the layering that may occur when a HUD (near layer) is superimposed on the external scene (far layer). One obvious difference is that in an aircraft the external scene is also moving, but presumably not in common fate with the movements of the HUD symbology.

The creation of two layers in the current paradigm is also what occurs when frame of reference (FOR) is mixed on HMDs. For example, the Technical Panel Two (TP2) symbology set includes both head referenced and aircraft referenced symbology. The head-referenced symbology is yoked to the pilot's head movements, whereas the aircraft symbology is yoked to the axis of the aircraft. Accordingly, when the pilot moves his/her head, the head-referenced symbology moves with the head and independently from the aircraft referenced symbols.

The object-based attention hypothesis is that attention can be allocated to the moving versus the static layers of dots. This should result in faster processing of elements within a layer as compared to across layers or in an unattended layer. To test this, subjects performed a same/different task where two of the dots changed to either the same or a different colour. The dots that changed were either from the same layer of on different layers. Subjects performed a series of trials where they attempted to focus attention on the moving layer and a series of trials where they focused attention on the static layer. The object-based attention was supported.

Method

Observers. Four observers participated in the experiment. Two had participated in Experiment 1.

Apparatus. The display was presented on a ViewSonic 17 inch colour monitor with .25 dot pitch (model PS790) controlled by a Cambridge Research Systems VSG 2/3 video board installed in a Pentium-powered IBM compatible computer. Observer responses were collected using a response box equipped with microswitches. The response box was connected to the VSG board. Response times were accurate to less than 1 ms.

Stimuli. The display consisted of seven light grey dots shown against a dark grey background at random positions. Four of the dots stayed stationary during a trial, whereas the other three dots moved in unison. At some point in the trial two of the dots in the display changed colour, either to red or to green. Each of these two dots was equally likely to be within the moving group or the stationary group. The whole display subtended roughly 14° of visual angle; each dot had a diameter of 0.3°. The moving dots had an elliptical trajectory: the trajectory's parameters (direction of rotation, high and width) were varied from trial to trial.

Design. There were 12 conditions in the experiment, which were defined by the 2 x 3 x 2 factorial combination of colour (same vs. different), location(moving layer, static layer, both layers) and attentional focus (moving layer vs. static layer). A completely repeated measures design was used in which all combinations of conditions were experienced by each observer.

Colour. There were two colour conditions: both target dots changing to the same colour (i.e., either red or green) versus each target dot changing to a different colour.

Location. There were three location conditions. Both target dots occurred within the moving layer of dots. Both target dots occurred within the static layer of dots. Or, one target dot within each layer.

Attentional focus. There were two focus conditions. Observers were instructed to focus attention on the moving layer of dots versus on the static layer of dots.

Procedure. A two-alternative forced-choice (2AFC) procedure was used. On each trial, the dots were displayed for a variable interval lasting between two and six seconds, during which time all dots remained light grey and the moving group of dots described their elliptical trajectory. At the end of the variable interval, two randomly selected dots in the display changed colour, while the moving dots continued their trajectory. The display with the coloured dots lasted until the observer responded, or until the display timed out after three seconds. The observers' task was to determine whether the two dots that had just changed colour had taken on the same or different colour (possible colours were red and green). Observers responded by pressing one button on the response box for a "same" judgement, and another button for a "different" judgement.

Each observer completed 6 blocks of 60 trials (total of 360 trials). Each block was initiated by the observer, whereas each trial was initiated automatically following a brief (2 sec.) pause. For each block, the observer was instructed to focus attention on either the moving layer of dots or on the static layer of dots. The order of attentional focus was counterbalanced across observers. Observers were to respond both as quickly and as accurately to the target (colour) dots.

Results

Mean reaction times on correct trials were computed for the 12 experimental conditions. Figure 5 shows latencies as a function of attention focus to the moving layer (panel a) versus the static layer (panel b). These latencies were analyzed with a 2 (colour: same vs. different) x 3(layer: moving layer, static layer, both layers) x 2 (attentional focus: moving layer vs. static layer) ANOVA with repeated measures on all factors. The ANOVA showed significant two-way interactions between layer and focus, $F(2,6) = 61.985$, $MSE = 694.700$, $p < .001$, layer and response, $F(2,6) = 7.716$, $MSE = 80.136$, $p < .05$, and a three-way interaction between layer, response and focus, $F(2,6) = 79.070$, $MSE = 182.740$, $p < .001$.

Of particular interest was the significant interaction between location and focus. As shown in Figure 1, response latencies to targets were markedly lower when the targets occurred in the attended layer. When attending to the moving layer (panel a) latencies were fastest to target dots that occurred in the moving layer, as opposed to the static layer or across (both) layers. In contrast, when attending to the static layer (panel b), latencies were faster to target dots that occurred in the static layer as opposed to dots occurring in the moving layer or across layers. This pattern was further supported in a separate ANOVA comparing latencies in the moving versus the static conditions which showed a significant interaction between layer and focus, $F(1,3) = 71.498$. $MSE = 483.932$, $p < .005$.

In sum, the present results show that observers were able to use common motion to partition the complete set of dots into moving versus static object layers and that

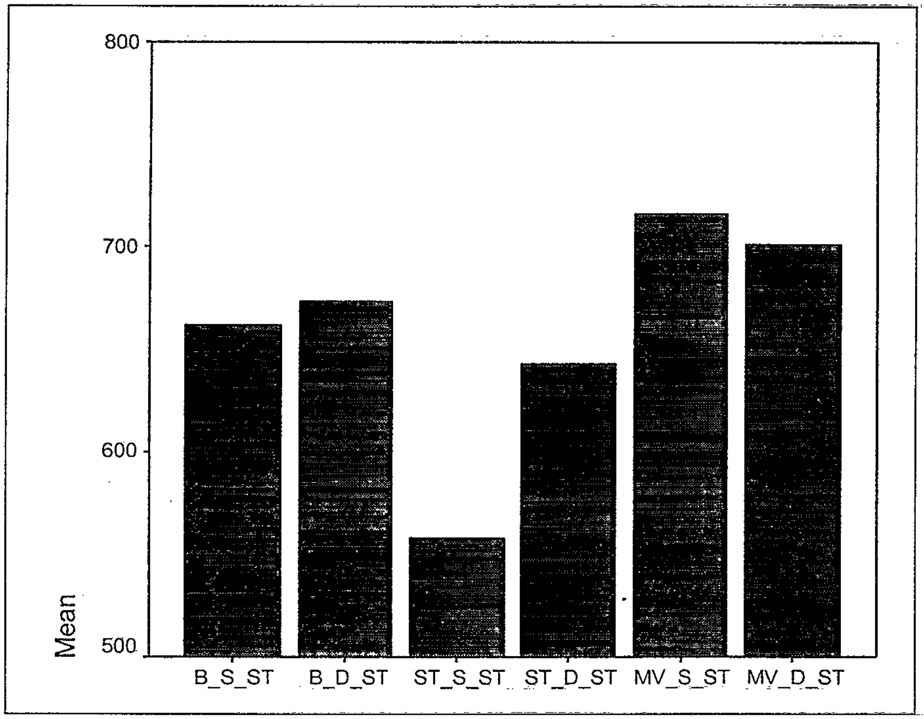

Figure 5a. Mean reaction times by condition of target for Experiment 5, focus on static layer. B_S_ST & B_D_ST: both layers; ST_S_ST & ST_D_ST: static layer; MV_S_ST & MV_D_ST: moving layer.

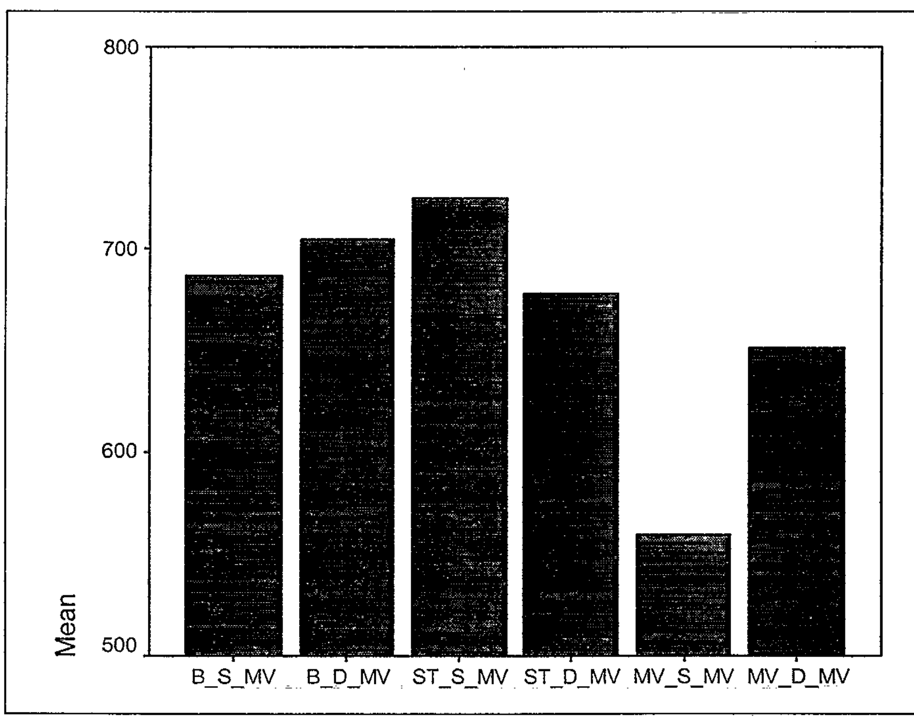

Figure 5b. Mean reaction times by condition for Experiment 5, focus on moving layer. B_S_MV & B_D_MV: both layers; ST_S_MV & ST_D_MV: static layer; MV_S_MV & MV_D_MV: moving layer.

attention could be strategically allocated to one or the other layer. The size of this object-based attention effect was substantial (80 ms on average) and appeared to be symmetrical. The mean latencies show that the advantage of the attended layer is reflected mainly in the condition where both of the target dots have the same colour. Responses to dots of the same colour were on average 100 ms faster than to dots of different colour in the attended layer. This same colour advantage is reversed when the target dots occur in the unattended layer. In this case, observers respond to dots of the came colour more slowly, on average by about 30 ms. The meaning of this reversal is unclear.

Discussion

The present results are consistent with the object-based attention hypothesis that elements within a single perceptual object will be processed more quickly than elements from more than one object. An important contribution of this research is in showing (a) that elements in multi-element displays can be partitioned into object layers through the use of common motion and (b) that attention can be effectively allocated to object layers in dynamic displays.

Several issues concerning the impact of object layering remain to be systematically examined. For one, it is not clear from the present experiment whether the object-layering effect is facilitating or inhibitory. Clearly, grouping elements by common motion favours the processing of elements within the group, but does this happen at the expense of an observer's ability to attend to the other parts of the display? To this end, a series of baseline conditions need to be developed to determine whether attending to an object layer speeds responses to targets in that layer, or whether attending to one layer functions to slow responses to target that occur outside the attended layer. This could have a major impact on the processing of warning signals or other unexpected events, which might happen outside of the layer being attended to, as is observed with cognitive tunnelling.

SECTION THREE

1. FINAL DISCUSSION AND SUMMARY

Traditional aircraft instrumentation set-ups, which force pilots to physically scan between their flight instruments and the external scene, have been associated with performance decrements in certain situations. To address this issue, heads-up displays (HUDs) have been developed which project symbolic representations of the flight instruments over the pilot's forward filed of view. Although HUDs have shown some promise in improving flight performance, they have also been associated with a number of attentional problems. These problems are generally associated with difficulties in dividing attention between the HUD symbology (the near domain) and the external scene (the far domain). It has been shown that pilots are more likely to miss unexpected events in the external scene while attending to the HUD, a phenomenon which has been attributed to cognitive tunnelling on the HUD symbology (Martin-Emerson & Wickens, 1997). Also, the sheer number of elements in the HUD symbology clutters the field of view and thereby makes it difficult for pilots to (a) use the information from the symbology in an efficient and integrated fashion and (b) look beyond the symbology to the external scene.

An object-based attention framework has been used to account for some of the attentional problems associated with HUDs. On this view, the HUD is assumed to form one perceptual group or object, which captures attention at the expense of attending to the external scene. In Experiment 1 of the present research, an object-based attention framework was established which allows for a systematic study of the factors which can interact with, and are often confounded with, object-based factors in the allocation of visual attention. This experiment showed that subjects' ability to process targets was determined by object-based factors rather than spatial factors. This finding is important because spatial and object-based attentional operators have often been confounded in research on HUDs (e.g. see McCann, Foyle, & Johnston, 1993). Experiment 2 examined the interaction of object-based attention and spatial cueing. The results showed that spatial cueing is able to capture attention at the expense of allocating attention to perceptual objects in the display. Experiment 3 investigated how the effectiveness of spatial cueing might be influenced by the cognitive salience of cueing. Subjects' attention was captured just as effectively whether or not they had been informed about the existence of the spatial cues and their relevance to the task. These results have implications for the use of warning signals and demonstrate that spatial and object-based factors can interact in unexpected ways in HUDs.

Experiments 4 and 5 examined the role of individual grouping principles in the allocation of attention to objects. Experiment 4 showed that subjects were able to allocate attention to individual perceptual objects regardless of whether they were distinguished by different colours. This is an important finding for HUD systems which must make use of a restricted range of colours; this is particularly true of NVGs, where both the symbology and the external scenery are displayed using the same colour. In Experiment 5, a step was taken toward the study of object-based attention in dynamic displays which more closely resemble actual HUD environments. Experiment 5 showed that subjects are able to attend to groups of objects that are segregated by common motion. This suggests that common motion might be a useful factor in improving the organization of HUD symbology.

The Experiment 5 finding that attention can be allocated to objects (or object layers) that are defined by common motion has direct implications for the Technical Panel 2 (TP2) symbology set. The TP2 set was developed for use in a head-tracked HMD. The TP2 set is configured as a mixed frame of references where some of the HUD symbology is referenced to the front and centre of the aircraft, whereas other symbology is referenced to the head movements of the pilot. According to Gestalt principles, the head-referenced (moving) symbology will be perceptually grouped in an object separate from the aircraft-referenced symbology. Importantly, and in accord with the object-based hypothesis, the results of Experiment 5 suggest that attention may be differentially allocated to head-referenced versus aircraft-referenced symbology. One potential outcome is that processing of head-referenced symbology may benefit from object-based attention. On the other hand, a potential disadvantage is that it may be harder for pilots to switch from processing the head-referenced symbology to processing the aircraft-referenced symbology. These possibilities need to be systematically explored.

2. FUTURE DIRECTIONS

To date, the current research program has established a viable framework for studying object-based attention and its relation to other factors. In addition, necessary preliminary steps have been taken toward the investigation of attentional control in HUD environments. This has involved the study of individual grouping principles and the use of dynamic displays.

Two parallel streams. The continuation of this line of research will involve work in two parallel and mutually supporting streams. One stream will involve the continued study of dynamic, more realistic displays in an experimental setting: this stream will include further research into the development of an object-based attention framework. The second stream will involve the application of the object-based framework to investigate HUD symbology in simulated flight. A concrete instance of this parallel stream approach has already been illustrated in the discussion of Experiment 5 and the experiments on the TP2 set. The TP2 experiments examined the impact of grouping elements of the symbology by common fate in a setting approximating actual flight conditions.

An important aspect of the TP2 symbology set is that the moving HUD symbologies are head-referenced. This raises the possibility that grouping by common motion might be further strengthened by the user controlling the motion of the elements. To this end, laboratory research is required to systematically isolate and assess the role of user-controlled motion in attentional control.

Another issue associated with the TP2 mixed-referencing configuration is to determine the conditions under which the head-referenced elements are useful versus the conditions where head-referencing might be detrimental to performance. In particular, it is unclear whether the facilitating effect of allocating attention to the head-referenced symbology inhibits the allocation of attention to other elements in the display, and to what extent this inhibition might be detrimental. This is, of course, a question about the fundamental nature of object-based attention. The effective visual processing of a scene, such as a HUD environment, requires the integration of information from many different elements in many different parts of the scene. It is known from the object-based attention literature that the integration of information is facilitated by the perception that the sources of that information constitute a coherent whole. The grouping of individual elements in a display into wholes is based on a number of grouping principles, such as grouping by proximity, grouping by colour, good continuation, and grouping by motion, to name a few. Thus, these principles can be put to good use to facilitate the integration of information. However, not all grouping principles are appropriate to all situations. For instance, grouping by colour cannot be used in NVG displays, as these are monochrome. By the same token, grouping certain elements of a symbology by common motion would be counterproductive if some of the elements are informative only in a fixed frame of reference.

In sum, making use of the object-based attention paradigm in the design and evaluation of HUDs requires a good theoretical understanding of the nature of the perceptual grouping and the effects of its various mechanisms and their interactions on attention. It is important to determine which grouping principles form the most coherent groups and the most object-like shapes. It is also important to determine the extent to which the coherence of these forms of perceptual grouping (degree of "objectness") related to the capturing and maintenance of attention. To this end, it would be useful to develop metrics of the coherence of perceptual elements. Such metrics will require an interdisciplinary approach, bringing together insights and methods from cognitive and perceptual psychology, neuroscience, artificial intelligence (in the form of computer vision) and philosophy.

In using an object-based approach to developing HUDs, it is important to index the hierarchy of grouping principles, where one perceptual grouping principle overrides others. Similarly, it is necessary to know whether a single grouping principle is sufficient for forming an object or whether more than one grouping principle must be put into place. It is possible that the addition of a second grouping factor to a HUD symbol will enhance the sense of the symbol's objectness. It is not clear, however, whether the extent of a symbol's "objectness" is related to degree of object-based attention assigned to the symbol. For instance, HUD symbologies that are too "strong" as objects may impact on cognitive tunnelling. Further, it is imperative to assess the relation between the influence of spatial cueing and object-based attention in dynamic contexts.

Summary. In sum, the research summarized in this report demonstrates that an object-based attention framework is a viable and useful approach for HUD research and development. The laboratory research that has been conducted compliments and directly impacts on the HUD development of HUD and HMD systems such as those proposed by the TP2 panel. The further development of HUD/HMD systems will benefit from the continuation of this parallel laboratory and simulator research program.

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